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Geology Of The Battle River Study Site: Plains Hydrology And Reclamation Project

Heritage Fund

Alberta

LAND CONSERVATION AND
RECLAMATION COUNCIL
Reclamation Research
Technical Advisory Committee

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GEOLOGY OF THE BATTLE RIVER STUDY SITE:
PLAINS HYDROLOGY AND RECLAMATION PROJECT

by

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of

The Alberta Land Conservation and Reclamation Council

March 1986

ALBERTA'S RECLAMATION RESEARCH PROGRAM

The regulation of surface distrubances in Alberta is the responsibility of the Land Conservation and Reclamation Council. The Council executive consists of a chairman from the Department of the Environment and two deputy chairmen from the Department of Energy and Natural Resources. Among other functions, the Council oversees programs for reclamation of abandoned disturbances and reclamation research. The reclamation research program was established to provide answers to the many practical questions which arise in reclamation. Funds for implementing both the operational and research programs are drawn from Alberta's Heritage Savings Trust Fund.

To assist in technical matters related to the development and administration of the research program the Council appointed the Reclamation Research Technical Advisory Committee (RRTAC). The Committee first met in March, 1978 and consists of eight members representing the Alberta Departments of Agriculture, Energy and Natural Resources, Environment and the Alberta Research Council. The Committee meets regularly to update research priorities, review solicited and unsolicited research proposals, arrange workshops and otherwise act as a referral and coordinating body for Reclamation Research.

Additional information on the Reclamation Research Program may be obtained by contacting:

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PREFACE

This is one of a series of reports that presents the findings of the Plains Hydrology and Reclamation Projects (PHRP), an interdisciplinary study that focuses primarily on hydrologic aspects of reclamation of surface coal mines in the plains of Alberta. This research has been conducted by the Alberta Research Council, as part of the Alberta Government's Reclamation Research Program. The program is managed by the Land Conservation and Reclamation Council and is supported by the Heritage Trust Fund.

The focus of the PHRP is to develop a predictive framework that will permit projection of success for reclamation and impact of mining on water resources on a long-term basis. The predictive framework is based on an understanding of processes acting within the landscape so that in the future, mine sites that are not totally analogous to those that have been studied can be evaluated as well.

The project involves a holistic approach to reclamation by integration of studies of geology, hydrogeology, and soils, not only in the proposed mining area, but also in the adjoining unmined areas. This approach permits the assessment of impacts and of long-term performance, not only in reclaimed areas, but also in the surrounding area.

The research of the PHRP has been directed toward the following two major objectives and eight subobjectives.

Objective A

To evaluate the potential for reclamation of lands to be surface mined. The focus is on features of the landscape that make it productive in a broad sense not restricted to revegetation. This objective was organized into five subobjectives.

1. To assess and evaluate the potential for long-term degradation of reclaimed soils through salt buildup.
2. To assess and evaluate the effectiveness of topographic modification and selective placement of materials to

mitigate deleterious impacts on chemical quality of groundwater.

3. To assess the availability of water supply in or beneath cast overburden to support post-mining land use, including both quantity and quality considerations.
4. To evaluate the productivity potential (capability) of post-mining landscapes and the significance of changes in capability as a result of mining.
5. To assess and evaluate limitations to post-mining land use posed by physical instability of cast overburden.

Objective B

To evaluate the long-term impact of mining and reclamation on water quantity and quality. This objective was organized into three subobjectives.

1. To assess and evaluate the long-term alteration of quality of groundwater in cast overburden and surface water fed from mine spoil as a result of the generation of weathering products.
2. To assess and evaluate infiltration, groundwater recharge, and groundwater-surface water interactions within cast overburden.
3. To characterize the groundwater chemistry generated within cast overburden.

Studies directed at these objectives began in 1979 at the Battle River site in east-central Alberta. Work began in 1982 at a second study area at Highvale Mine south of Lake Wabamun. Significant progress had been made on all project objectives by the end of the first phase of study in March 1984. This present series of reports summarizes the state of our knowledge at the end of this first phase of study. Work is now continuing on the Phase II objectives to gain an even greater understanding of the complex physical and chemical processes in reclaimed landscapes.

The following report deals with studies directed at Subobjective A-2: To assess and evaluate the effectiveness of topographic modification and selective placement of materials to mitigate deleterious impacts on chemical quality of groundwater. This report summarizes the geology of the Battle River site. The report was prepared from data collected from 1979 through 1982. The geologic base as it exists prior to mining provides the framework within which hydrologic, chemical, and soil systems operate. The physical characteristics of the strata have been determined in order to understand fully the hydrogeological and chemical data collected from the overburden. By interpreting geological strata in terms of the environment of deposition, a three-dimensional picture of the overburden has been produced. An understanding of the spatial distribution of specific stratigraphic units possessing certain physical and chemical properties aids in the understanding of how geological, hydro-geological, and geochemical systems are interrelated and how they have evolved.

ABSTRACT

The Battle River study site is underlain by rocks of the Bearpaw and Horseshoe Canyon Formations of Late Cretaceous age. The Bearpaw Formation consists dominantly of marine shale, but contains three laterally continuous sandstone beds. In the study area, at least 75 m of rock of the Bearpaw Formation is present. The upper shale unit of the Bearpaw Formation grades upward into siltstone and finally sandstone of the Horseshoe Canyon Formation. Above this basal sandstone, the Delta Sandstone, the Horseshoe Canyon Formation consists of complexly interbedded and intertongued beds, tongues and lentils of siltstone, shale and sandstone. Three laterally continuous coal beds characterize the formation in the Battle River study area. The lowest coal, the Battle River Bed, which rests on the Delta Sandstone, generally consists of two seams separated by a thin parting. Three coarsening-upward cycles that grade from shale to sandstone and have an aggregate thickness of 10 m to 12 m overlie the Battle River Bed and are capped by the second coal, the Marker Bed. This coal, which is present throughout the study area, ranges in thickness from 0.15 m to 0.5 m. The Paintearth Bed, which lies about 6 m to 10 m above the Marker Bed, consists of two to three individual seams separated by partings. At the southwestern edge of the study area, as much as 40 m of overburden of the Horseshoe Canyon Formation overlies the Paintearth Bed. Over most of the study area, the Horseshoe Canyon Formation is covered by from 1 to 10 m of Pleistocene glacial drift, consisting dominantly of silty till. In the low, flat area along and west of Highway 855 in the western part of the study area, the drift includes as much as 8 m of sand in two units. The lower sand unit separates two distinct beds of till in the area just west of Vesta Mine. The surface of the upper bed of till is discontinuously veneered by as much as 1 m of sand throughout the same part of the study area.

The coal-bearing strata at the Battle River site include sediments of marginal marine and deltaic environments. During late

Campanian time, repeated marine transgressions and regressions resulted in intertonguing of marine shale and sheets of sand that accumulated in near-shore environments. With time, an increase in sediment supply caused a large deltaic complex to migrate over the area. One lobe of this complex formed the platform on which the peat deposit that became the Battle River Bed was formed. The locus of sedimentation shifted and major distributaries developed to the north and south of the study area. Continued subsidence and a lack of sediment entering the study area resulted in formation of an interdistributary bay, which was episodically filled with crevasse splay deposits. The Marker Bed and Paintearth Bed were formed as coastal swamp deposits developed on this bay fill when the fill reached a level allowing vegetation to develop. These swamp deposits were then buried by a sequence of clastic sediment deposited in deltaic and near-shore environments that continued to occupy the area into mid-Maestrichtian time.

ACKNOWLEDGEMENTS

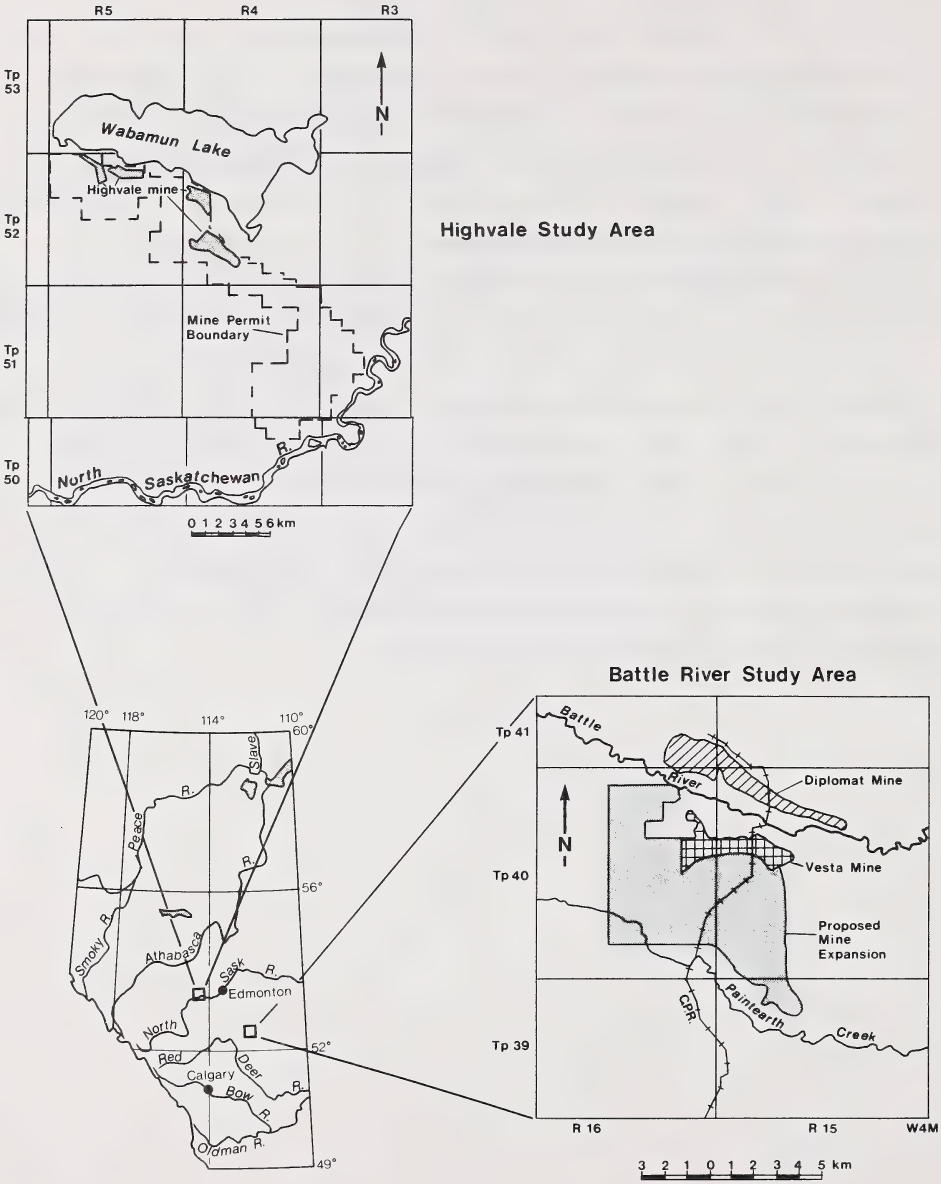
The research undertaken by the PHRP was supported with funds from the Heritage Savings Trust Fund. The research was done for the Land Conservation and Reclamation Council of the Alberta Government.

Geologic data and land access were provided by Alberta Power Ltd., Luscar Ltd., Manalta Coal Ltd., and landowners in the area.

1. INTRODUCTION

This report summarizes the geological setting of the Battle River study site (Figure 1). It is designed to provide a general understanding of geological conditions adequate to establish a framework for hydrogeological and general reclamation studies. The report is not intended to be a detailed synthesis such as would be required for mine planning purposes.

The primary data utilized in developing this report are 35 geophysically logged testholes and 10 coreholes that were drilled as part of the PHRP study (Figure 2). Project geologists also conducted detailed studies of measured sections in the badlands along Paintearth Creek and in mine highwall exposures. Additional data were provided by about 750 geophysically logged testholes on 200 m centres provided by Luscar Ltd. These logs and the cross-sections developed from them by Luscar were utilized to refine our understanding of the variations in thickness of coal seams and partings and in defining drift thickness.



Highvale Study Area

Battle River Study Area

Figure 1. Map showing location of PHRP study sites in the Battle River mining area and Lake Wabamun mining area, central Alberta.

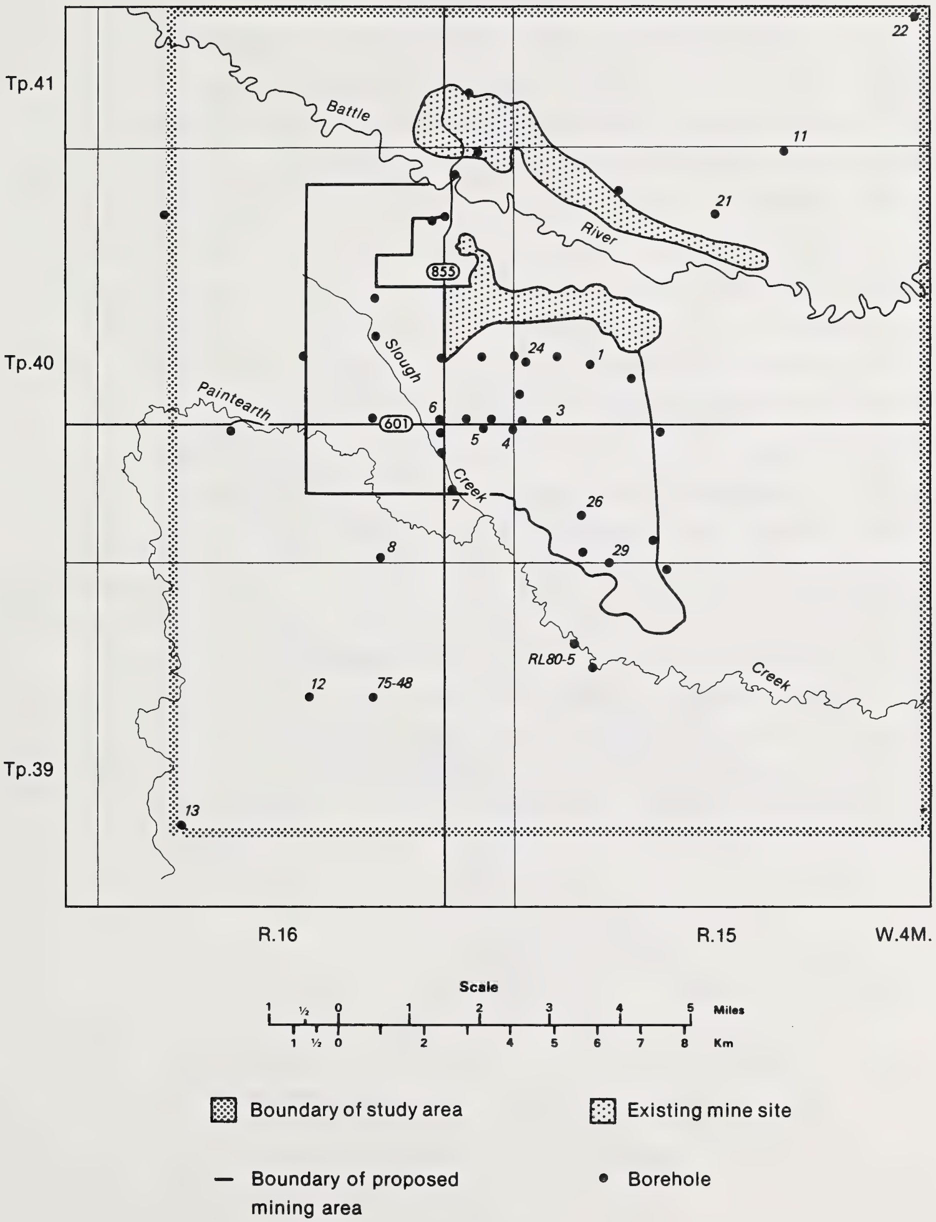


Figure 2. Map of Battle River study area showing location of PHRP boreholes and selected outcrop sections. Numbered boreholes are discussed in the text or appear on cross sections elsewhere in the report.

2. REGIONAL STRATIGRAPHIC SETTING

Upper Cretaceous marine and nonmarine sediment of the Bearpaw and Horseshoe Canyon Formations crops out along the Battle River in east-central Alberta (Figure 3). Where post-glacial channels have scoured deep valleys, the transitional boundary between the two formations is exposed. This boundary is everywhere diachronous (Allan and Sanderson 1945). The marine shale of the Bearpaw Formation represents deposition into the Cretaceous Sea of Late Campanian and early Maestrichtian time that inundated the central corridor of North America (Williams and Stelck 1975). The overlying Horseshoe Canyon Formation forms a wedge of easterly prograding continental sediment deposited in marginal marine and fluvial environments. The sediment dips gently to the west at a rate of about 3 m/km. The Horseshoe Canyon Formation is host to most of the known coal deposits in the Alberta plains. The coal seams within the formation have been identified at various localities, however, no study to date has resulted in a reliable correlation of the coal seams between areas in central Alberta. This situation results from the lack of continuous marker horizons and palaeontological remains within the sediments. For the purposes of this study, informal names have been assigned to distinct beds within the study area.

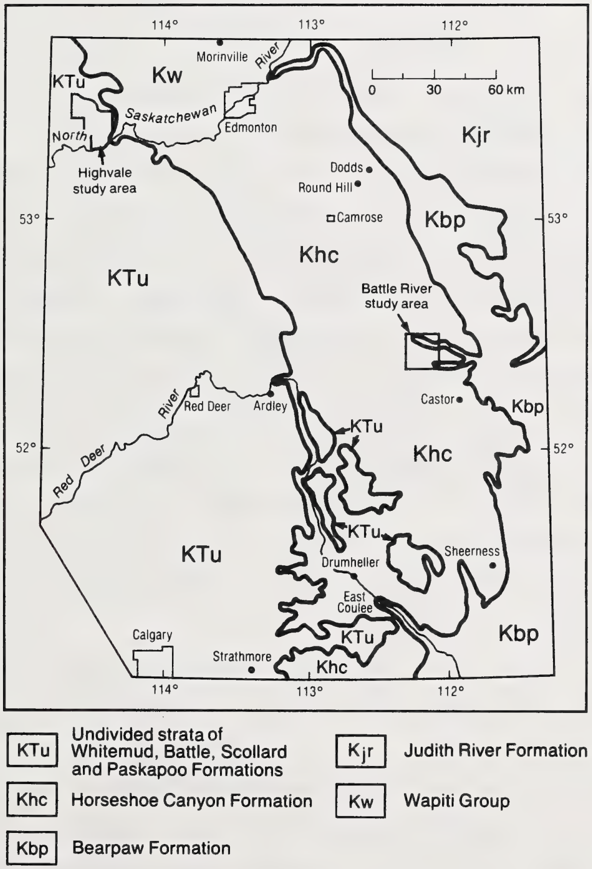


Figure 3. Map showing location of the Battle River study area in relation to the distribution of the Horseshoe Canyon Formation and location of important studies of these rocks.

3. BEARPAW FORMATION

The Bearpaw Formation consists mainly of dark grey weathering to brownish grey, marine shale, and fine- to medium-grained sandstone that are commonly glauconitic (Given and Wall 1971). Bands of clay ironstone concretions are present in places. Bentonite beds are common and are useful as local markers. The thickness of the formation decreases in a northerly direction from a maximum of 335 m (1100 ft) in the Cypress Hills area to 143 m (470 ft) in the vicinity of Castor (Given and Wall 1971). The Bearpaw Formation thins to the north, northwest, and west where it passes vertically and laterally into nonmarine sediment of the Horseshoe Canyon Formation (Ower 1960; Habib 1981).

Three laterally continuous sandstone and siltstone units, each underlain by marine shale, are identified within the study area (Figure 4). The lowermost sandy unit, referred to as the Basal Sandstone, varies in thickness between 7 m and 12 m. Next up section is the Deep Sandstone, which ranges in thickness between 4 m and 15 m (Figure 5). The third unit is the Middle Sandstone which varies in thickness between 6 m and 20 m (Figure 6). The Middle Sandstone is poorly developed at some sites within the study area and occurs instead as two or three sandy lenses interbedded with silt. Geophysical logs depict the Basal and Deep Sandstones as massive sandstone units with few shale interbeds. The contacts between the Basal and Deep Sandstone units and the underlying and overlying shale are relatively abrupt (Figure 7).

In the study area, the Deep Sandstone forms a lobate wedge that is thickest in the west (15 m) and thins towards the east (4 m) (Figure 5).

The main area of thick sand deposition in the Middle Sandstone forms a triangular lobe in the north-central part of the study area; fingers of thick sand extend toward the northwest, southwest, and northeast (Figure 6).

Overlying the Middle Sandstone is marine shale containing lenses and tongues of siltstone and silty sandstone. The marine

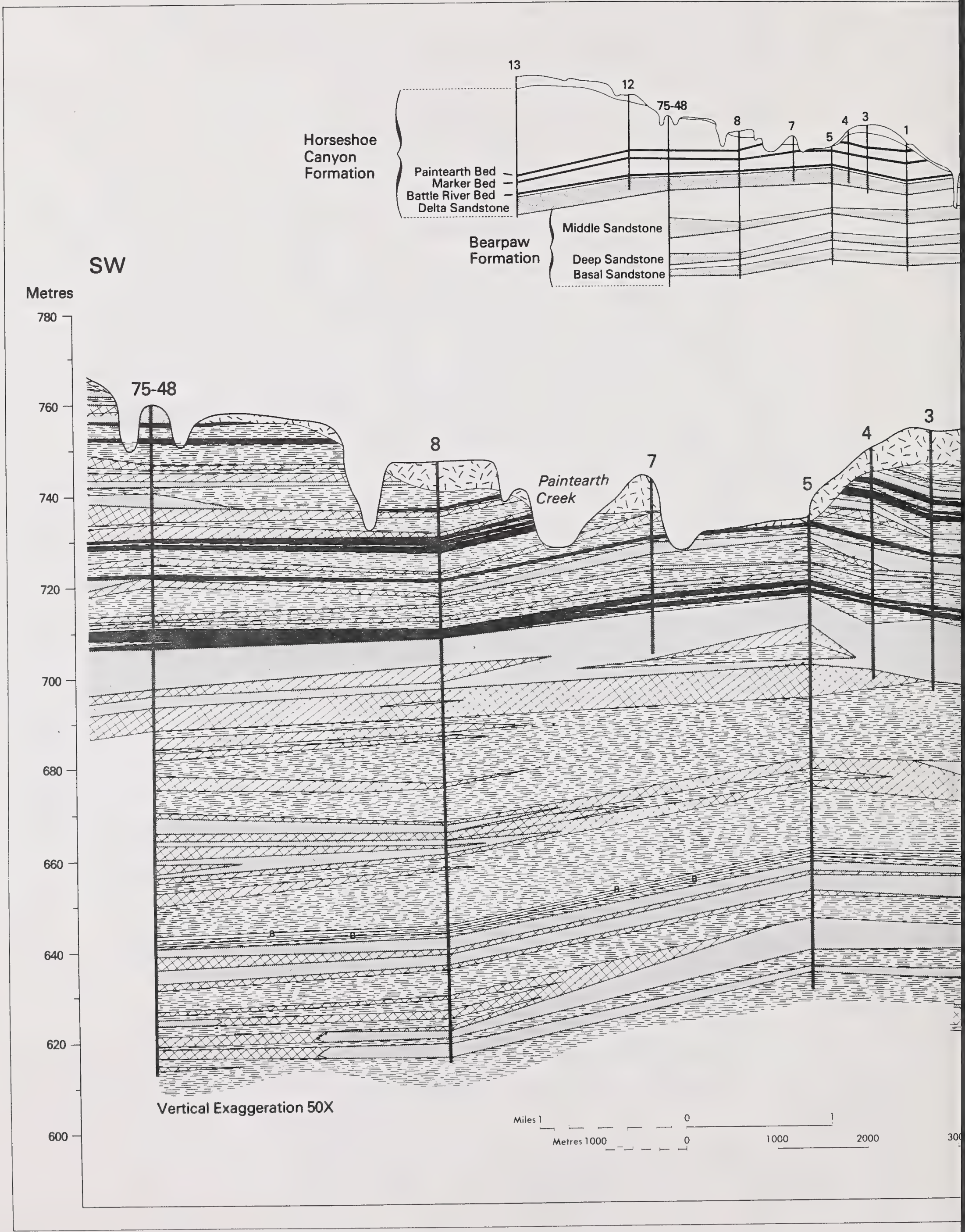
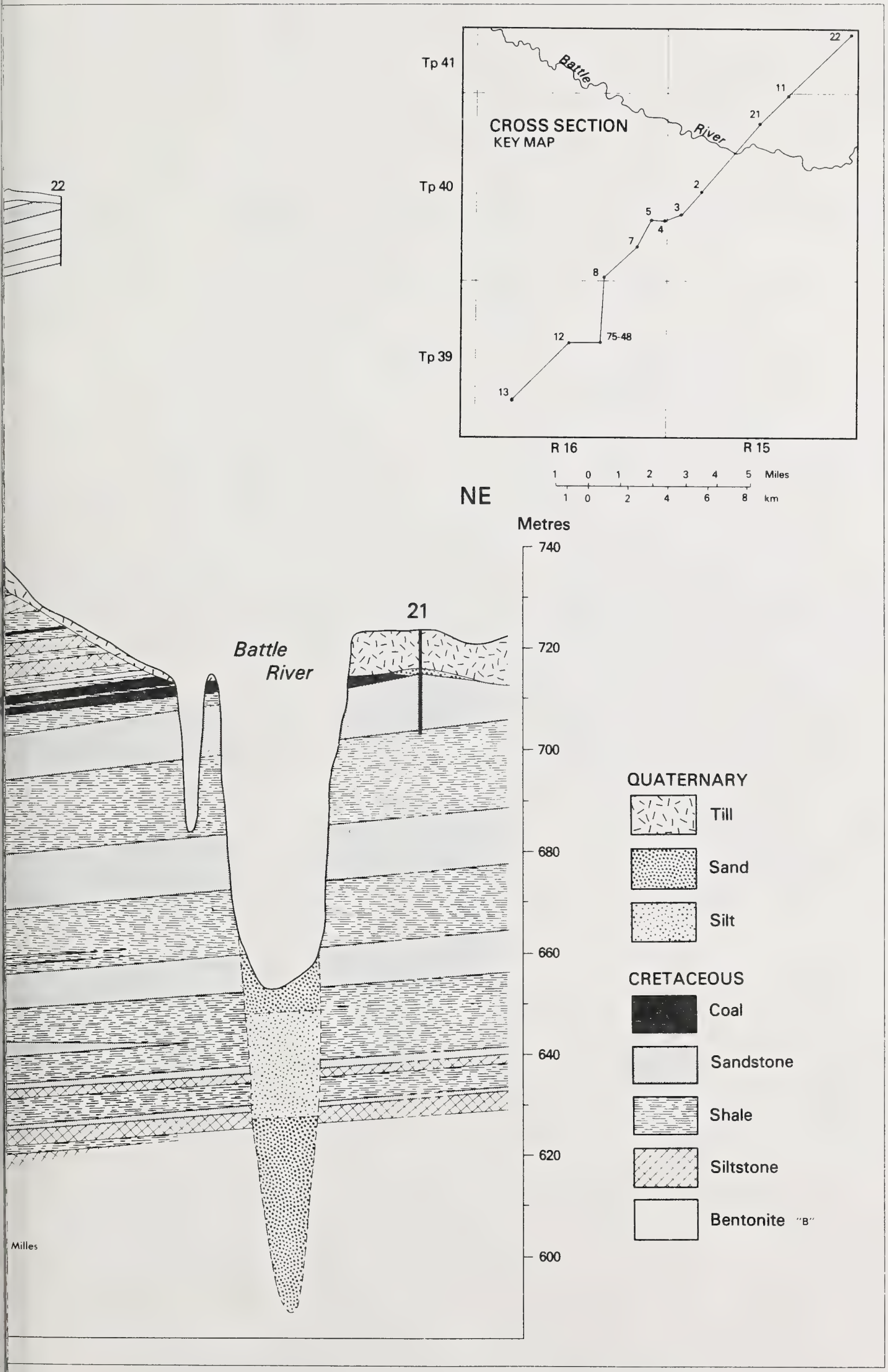


Figure 4. Northeast to southwest stratigraphic cross section through the Battle River study area.


CROSS SECTION
KEY MAP
Battle
River
Tp 41
Tp 40
Tp 39
R 16
R 15
22
11
21
2
3
4
5
7
8
12
75-48
13
1 0 1 2 3 4 5 Miles
1 0 2 4 6 8 km
NE
Metres
740
720
700
680
660
640
620
600
22
21
Battle
River
Milles
QUATERNARY
Till
Sand
Silt
CRETACEOUS
Coal
Sandstone
Shale
Siltstone
Bentonite "B"

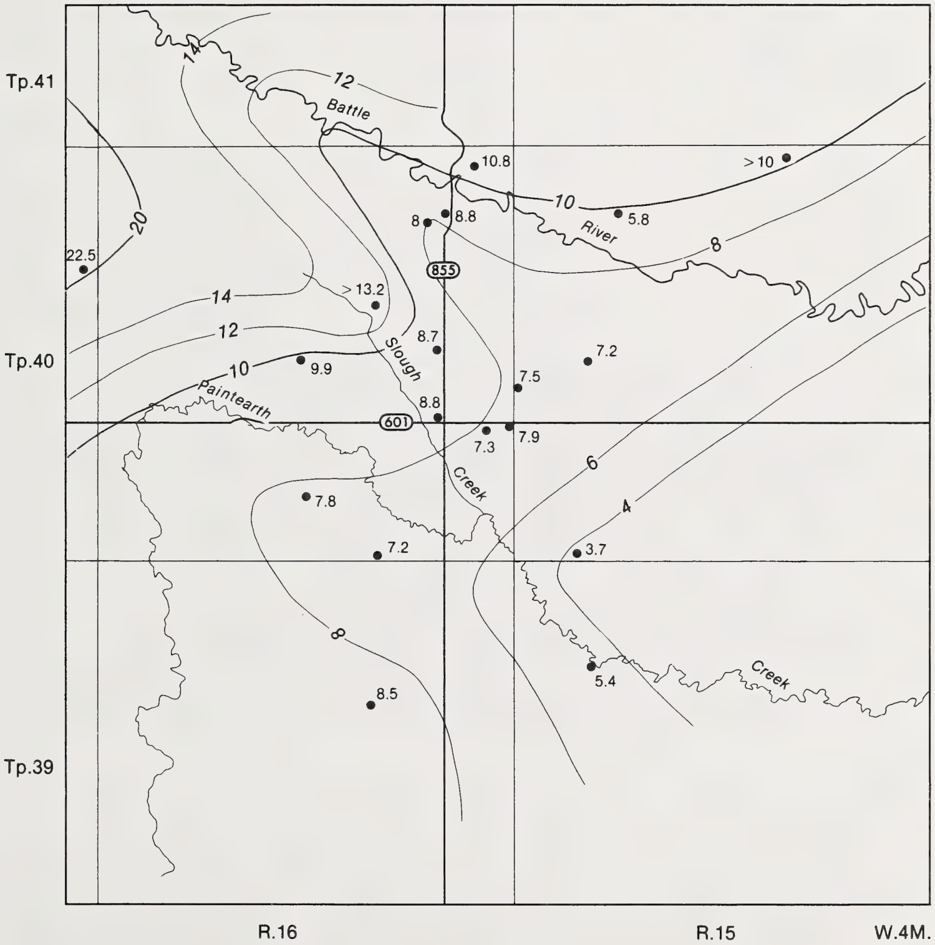


Figure 5. Map showing the thickness of the Deep Sandstone in the Battle River study area. Contour interval is 2 metres.

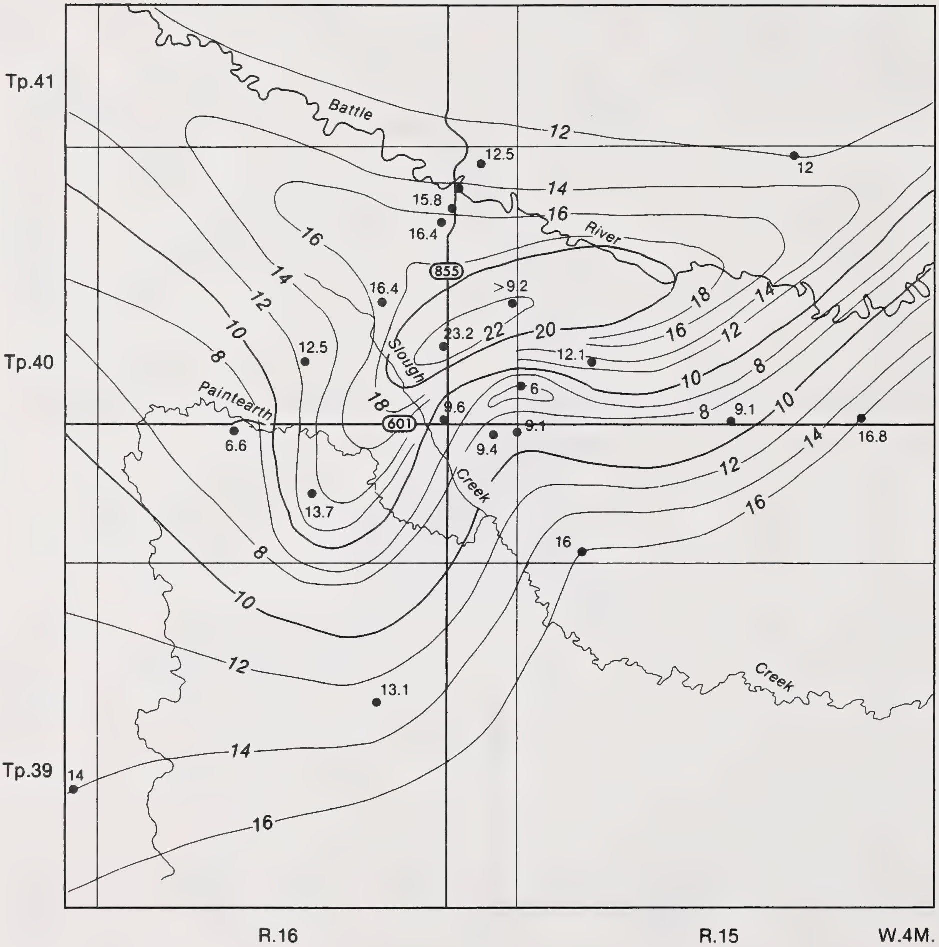


Figure 6. Map showing the thickness of the Middle Sandstone in the Battle River study area. Contour interval is 2 metres.

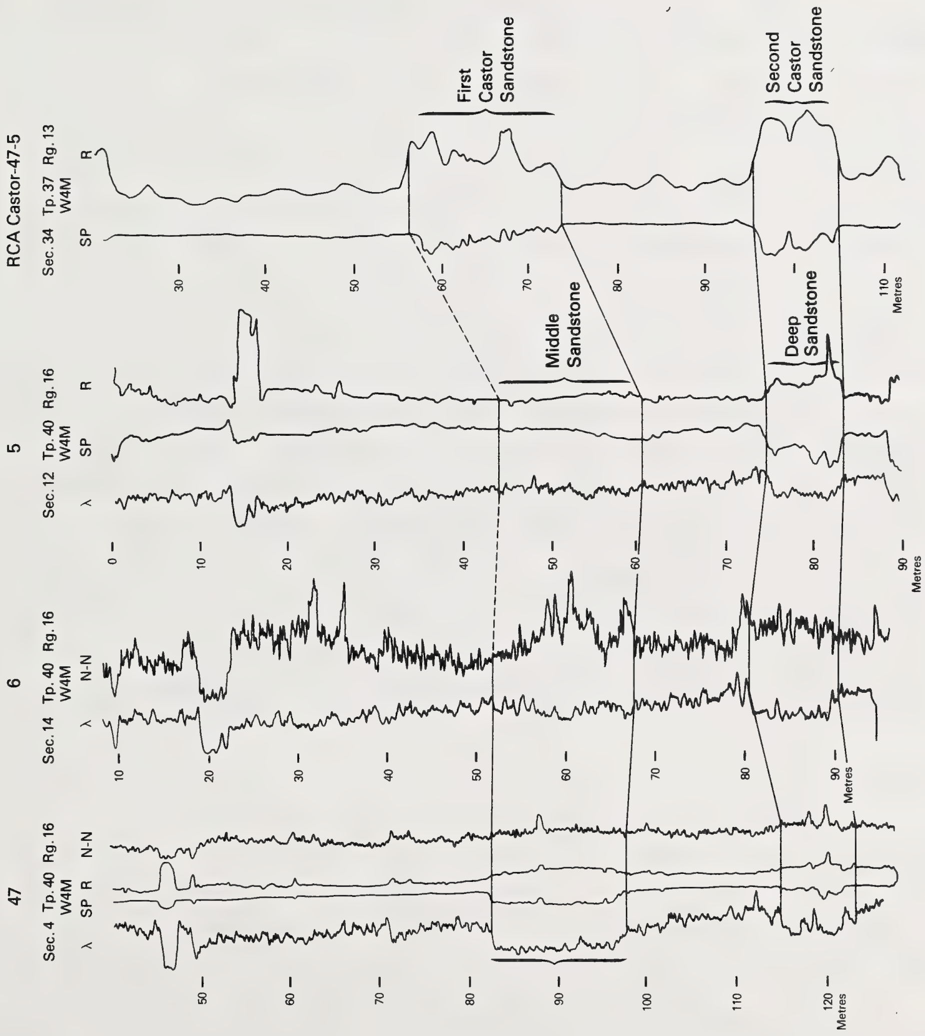


Figure 7. Stratigraphic section showing correlation of the Middle and Deep Sandstone units in the Battle River study area with the First and Second Castor Sandstones respectively in the Castor well of Given and Wall (1971).

shale grades upward into very argillaceous siltstone, and then into siltstone and fine-grained sandstone of the Horseshoe Canyon Formation. The transitional boundary between the Bearpaw and Horseshoe Canyon Formations occurs between 30 and 69 m depth within the study area (Figure 4).

Lines (1963) described two sand units within the upper member of the Bearpaw Formation exposed along Paintearth Creek near Castor. The lower sand, a medium-grained, glauconitic, "marine" type about 9 m (30 ft) thick, was believed to be the equivalent of the Bulwark Sandstone of south-central Alberta. The upper sand was described as 9 m (30 ft) thick, bentonitic, white-weathering and typically "nonmarine". Given and Wall (1971) correlated the Second Castor Sandstone in the Castor well (Lsd 13, Sec 34, Tp 37, R 13, W 4Mer) with the sandstone designated by Lines as Bulwark, and the First Castor Sandstone with the upper "nonmarine" sand. Habib (1981) correlated the Bearpaw Formation in south-central Alberta with the sandstone intervals of depositional cycles D and E of the upper Bearpaw Formation in south-central Alberta with the Bulwark Sandstone and the First Castor Sandstone, respectively. On the basis of correlation of log signatures, thickness and stratigraphic position, the Deep Sandstone of the study area seems to be the equivalent of the Bulwark or Second Castor Sandstone. The Middle Sandstone corresponds to the "nonmarine" or First Castor Sandstone (Figure 7).

4. HORSESHOE CANYON FORMATION

The Horseshoe Canyon Formation consists mainly of deltaic and fluvial deposits of interbedded grey and brown bentonitic shale and white and light grey salt-and-pepper feldspathic sandstone. The lower part of the formation contains a large number of coal seams and beds of carbonaceous shale. A well developed basal sand separates the Horseshoe Canyon Formation from the marine shale of the Bearpaw Formation. In the study area, this basal unit, which is informally called the Delta Sandstone, consists of upward coarsening siltstone and sandstone that varies in thickness from 8 m to 22 m (Figure 8). Large scale cross-beds are developed within the sand beds. The base of the Horseshoe Canyon Formation in the study area was delineated along the base of the siltstone portion of this unit.

An economic coal-bearing horizon, the Battle River Bed, caps the Delta Sandstone in the study area. The Battle River Bed contains as much as 3.9 m of sub-bituminous coal. The coal is divided, in most places, into two seams by a parting that varies in thickness from 0.5 m to 1.5 m. In the western half of the study area, the coal is wedge-shaped and thins rapidly toward the west (Figure 9). Through the central part of the study area, the coal is generally between 2 m to 3 m thick. The amount of noncoal partings within the coal in the southeastern and western part of the study area increases markedly. In the western part of the area, parting content increases abruptly from less than 10% to more than 60% within 800 m (Figure 10). In the southeast corner of the study area, the coal is less than 2.5 m thick (Figure 10) and the percentage of partings within the bed increases from less than 20% to more than 75% in a north-south direction (Figure 10).

The distribution of coal and partings within the Battle River Bed suggests that sediment was brought into the area from the northwest, west and south. Disturbed beds of Ostrea glabra, a species restricted to brackish water, have been identified in outcrop near the base of the Battle River Bed, in the Paintearth Creek badlands at the southern edge of the deposit.

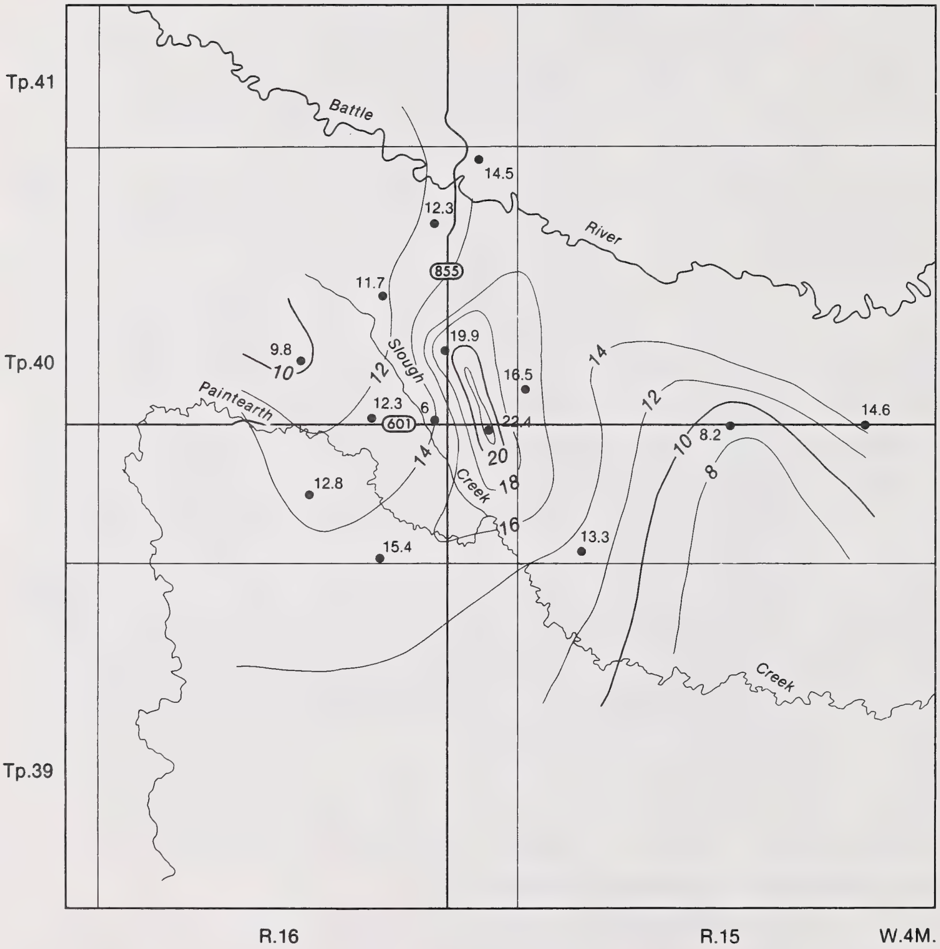


Figure 8. Map showing the thickness of the Delta Sandstone in the Battle River study area. Contour interval is 2 metres.

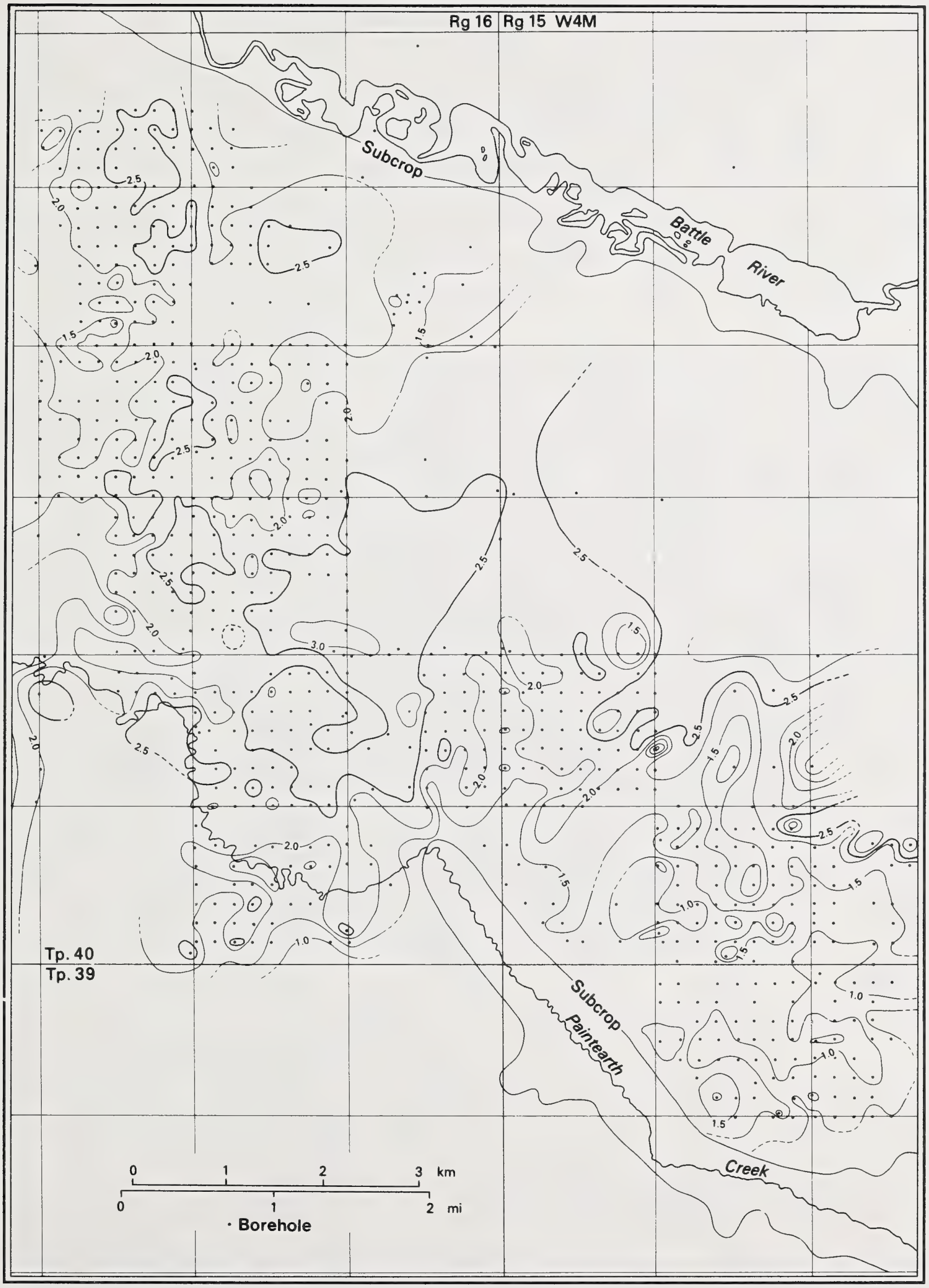


Figure 9. Map showing the thickness of the Battle River Bed in the central part of the study area. Contour interval is 0.5 metres.

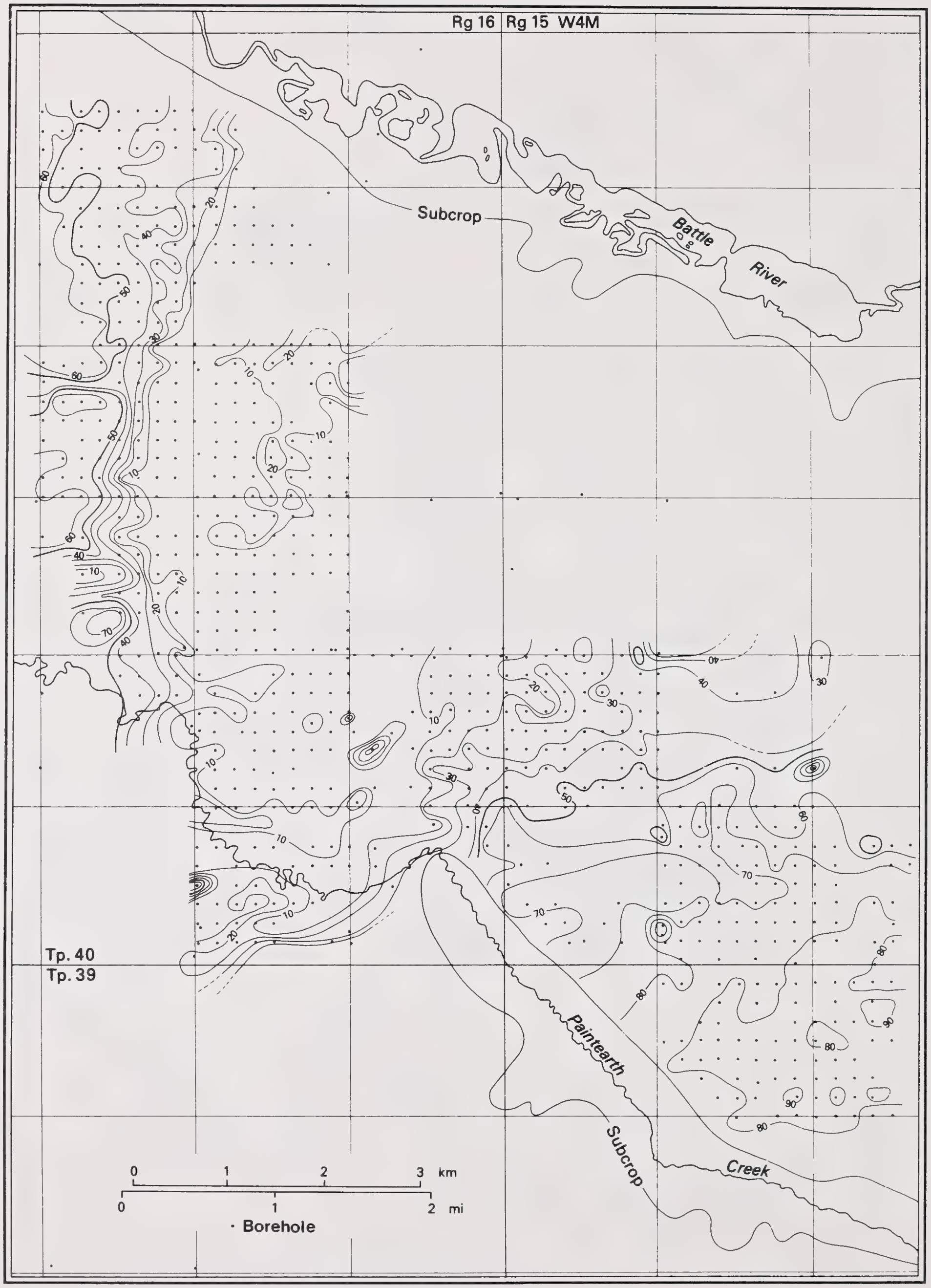


Figure 10. Map showing amount of parting in the Battle River Bed in the central part of the study area. Contour interval is 10 percent.

Overlying the Battle River Bed are brown shale and siltstone and light grey, fine-grained sandstone of the Battle River Interval. Organic fragments are abundant throughout all lithologies of this interval. Three coarsening upward cycles have been recognized within the interval in mine highwall exposure (Figure 11). Coarsening upward cycles are a product of river waters debouching into relatively still-standing and open bodies of water. Signatures on geophysical logs confirm the presence of these cycles throughout the study area (Figure 12).

Cycle 1 of the Battle River Interval is approximately 2 m thick and grades upward from shale to sandstone; the grain size of the sandstone varies between localities. A small, mud-filled channel cuts into the sandstone of the first cycle at RL80-5 (Figure 2) along Paintearth Creek. A thin, carbonaceous shale or coal lens caps the first cycle at some localities. The second and third cycles of shale grading upward into sandstone measure as much as 6 m and 7.5 m thick, respectively. The sandstone units capping the second and third cycles are commonly cross-bedded. These three coarsening upward cycles are laterally continuous and persistent throughout the study area, though the thickness of individual units within each cycle varies.

The Battle River Interval is capped by the next mappable coal horizon, the Marker Bed. Although everywhere less than 0.5 m thick, this coal bed is continuous and laterally persistent (Figure 12).

Shale below and above the Marker Bed contains abundant species of Deflandrea, a marine to brackish water species, that occur in the lowermost part of the Horseshoe Canyon Formation (Singh 1982, personal communications) (Figure 11).

The Marker Bed is overlain by the Marker Interval, which is between 6 m and 12 m thick and consists of interbedded shale, siltstone, and sandstone. The shale is brown and contains abundant organic material. The sandstone is light grey to grey and exhibits a salt-and-pepper texture. Some sand beds contain abundant organic

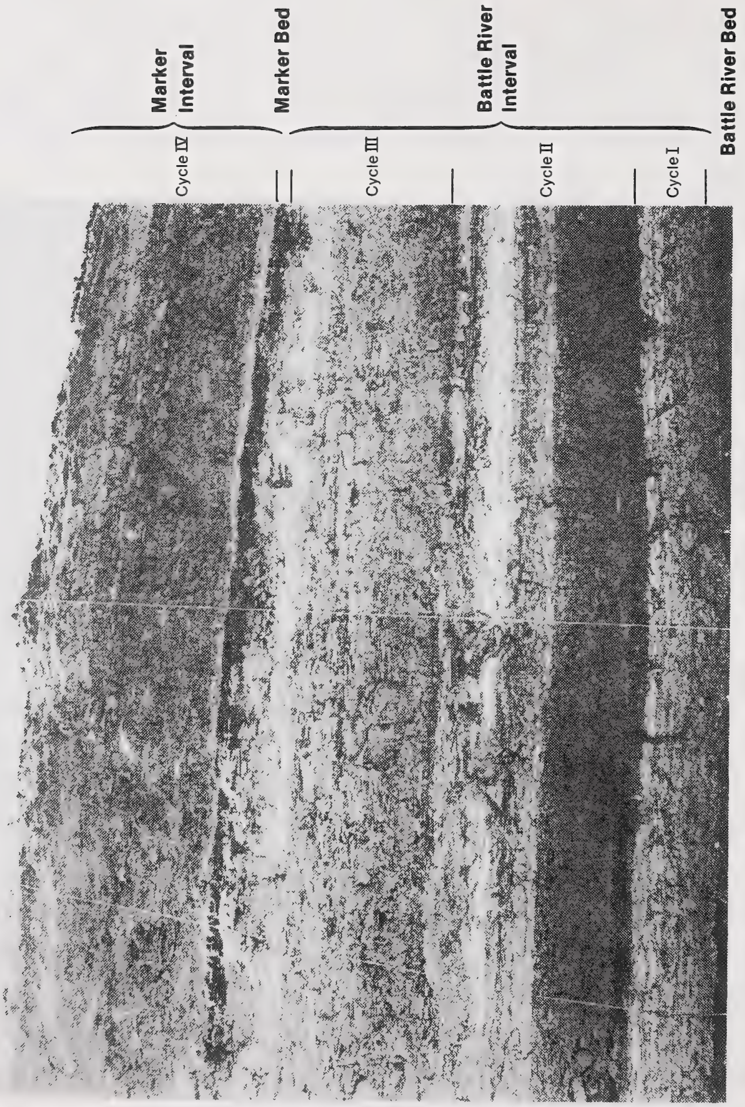
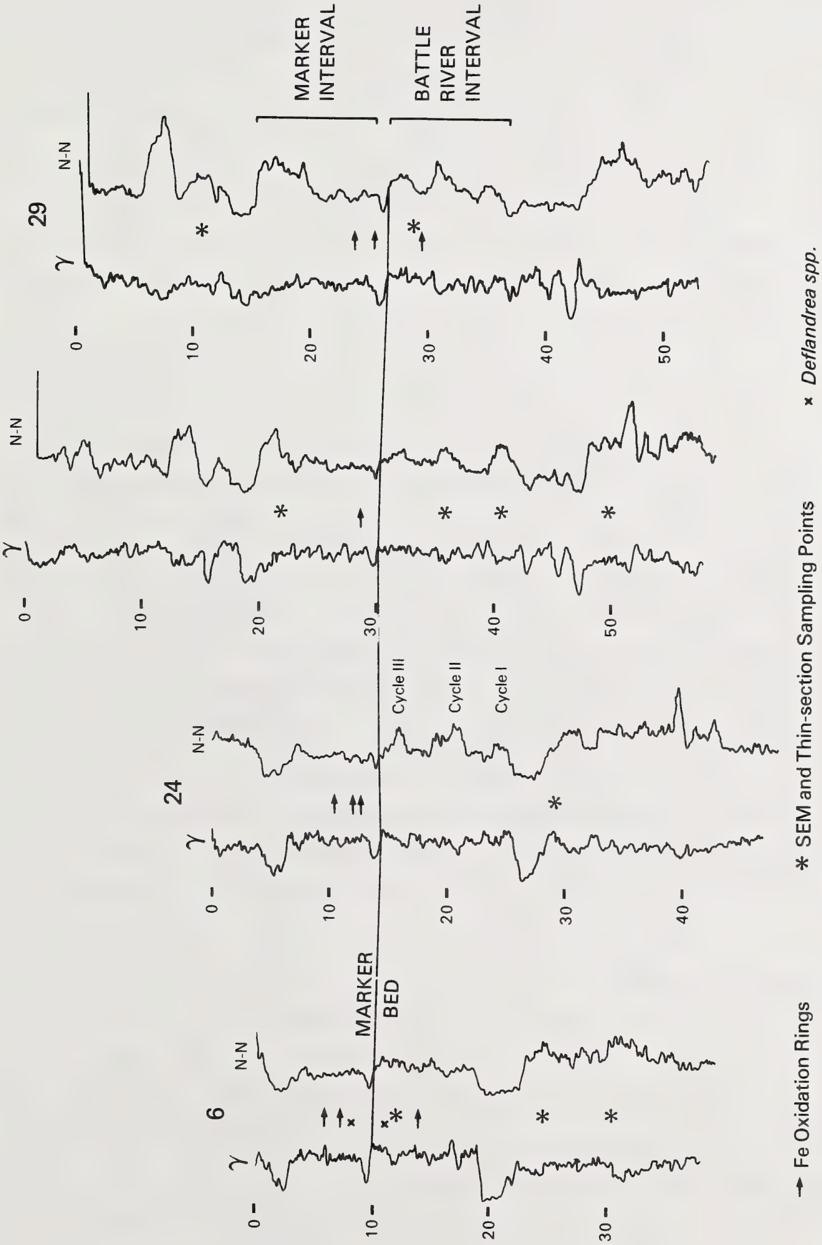


Figure 11. Mine Highwall Exposure showing Battle River Bed at base overlain by Battle River Interval, Marker Bed and Marker Interval



Geophysical logs of coreholes showing the three coarsening upward cycles of sedimentation within the Battle River Interval. Occurrences of iron oxidation rings are restricted to the Battle River and Marker Intervals.

Figure 12. Stratigraphic section illustrating geophysical log characteristics of the three coarsening upward cycles in the Battle River Interval.

laminae, especially those lower in the unit; other sand beds are cross-bedded and cemented, forming resistant ledges in outcrops along the valley of Paintearth Creek. At some outcrop localities, two or three coarsening upward cycles are identified in the Marker Interval, whereas at other localities, a single coarsening upward cycle is developed. In the southern part of the study area, only one coarsening upward cycle, which is about 10 m thick, is developed within this interval; it is capped by a resistant, massive sandstone about 5 m thick that pinches out to the east.

The Paintearth Bed, the second economic coal-bearing horizon in the area, overlies the Marker Interval. In most places, the main seam is interrupted by one parting that is 0.3 m thick. Another thin coal seam about 0.5 m thick overlies the main seam. The Paintearth Bed is thickest in the south-central portion of the study area, where it ranges in thickness between 2 m and 4 m, but it is generally greater than 3 m thick (Figure 13). The percentage of partings within the bed in this area is less than 50% (Figure 14). In the western half of the study area, the Paintearth Bed averages about 2 m thick and is interrupted by more than 50% partings over most of its occurrence. The greater abundance of partings in the coal to the west suggests that clastic sediment entered the swamp from the west, whereas the coal in the south-central portion of the study area formed in an environment more distant from a sediment source. As a result of post-glacial fluvial erosion, the Paintearth Bed is absent throughout the central part of the study area. It is, therefore, not possible to ascertain the geometry of this coal bed over the entire area. It can be observed however that near the erosional boundary, the percentage of partings associated with the coal is low, which suggests that coal in this area initially formed some distance from a source of sediment.

The overlying Paintearth Interval consists of both coarsening upward and fining upward cycles. The coarsening upward cycles are dominated by brown organic shale that grades upward into siltstone and cross-bedded, light grey, fine-grained sandstone.

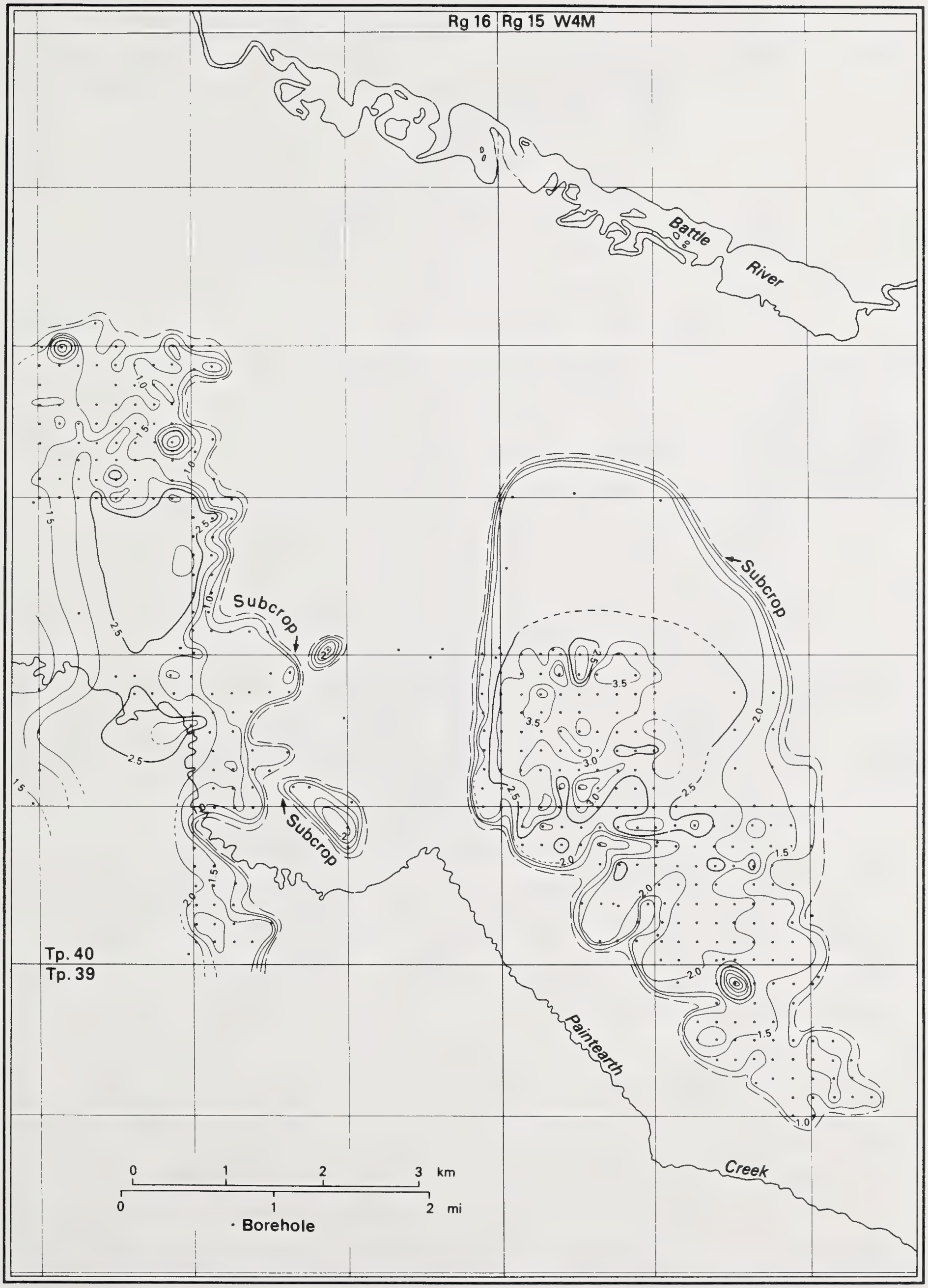


Figure 13. Map showing the thickness of the Paintearth Bed in the central part of the Battle River study area. Contour interval is 0.5 metres.

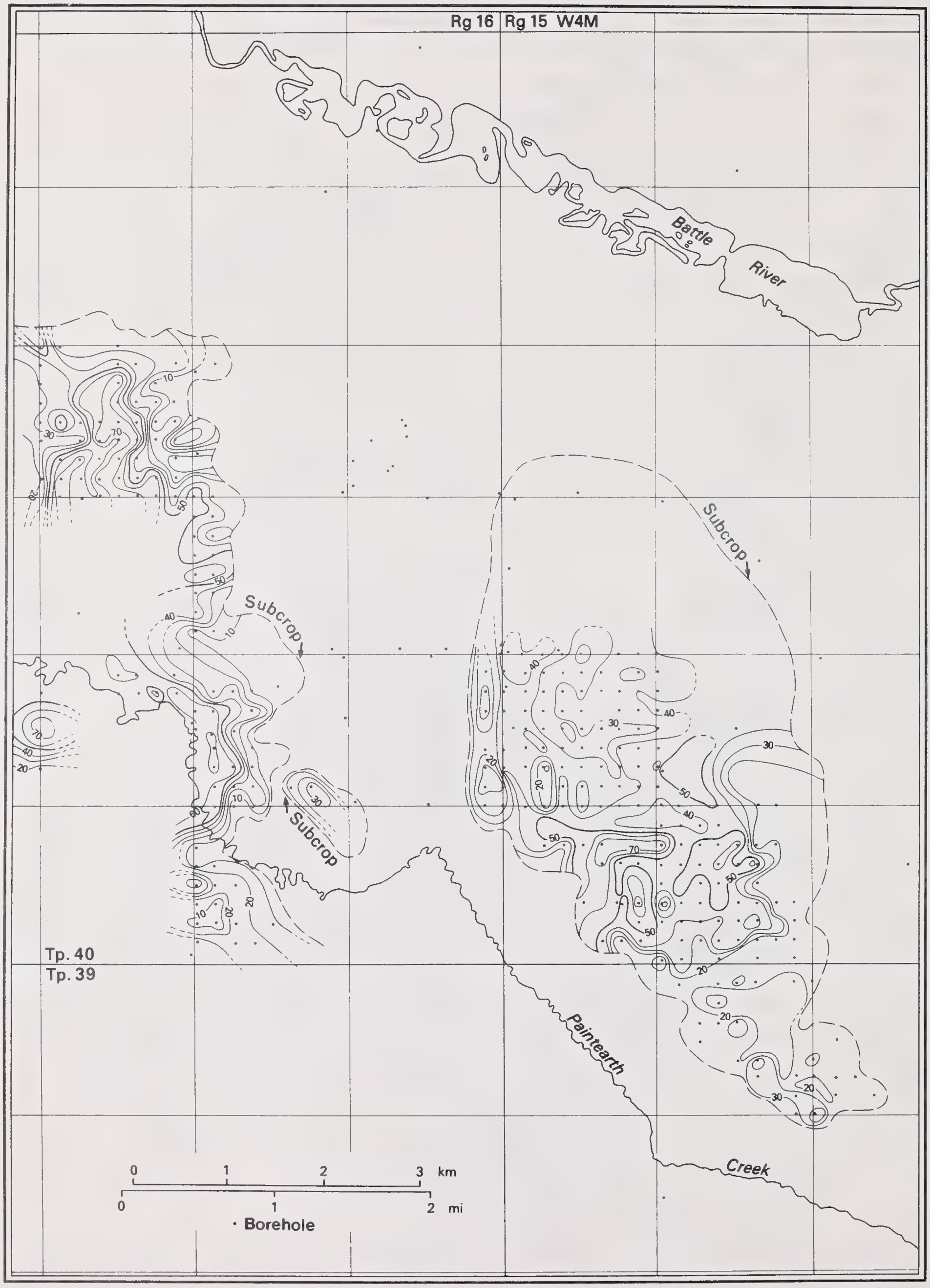


Figure 14. Map showing the amount of parting in the Paintearth Bed in the central part of the Battle River study area. Contour interval is 10 percent.

Fining upward cycles consist of medium-grained sandstone at the base grading abruptly upward through silt to grey and brown shale. Small sand-filled channels also occur within the interval.

4.1 MINERALOGY AND PETROLOGY

The Lower Horseshoe Canyon Formation in the study area is characterized by sediment with very high clay-to-sand ratios. Particle size analyses of 155 samples that were done by the standard hydrometer method by NorWest Laboratory Ltd. (McKeague 1978), indicate that clay sized particles comprise more than 31% of all samples from strata below the glacial drift (Figure 15). In 9 of the 11 strata delineated, very fine- to fine-grained sand comprises the second most abundant fraction of the samples (Maslowski Schutze, in press). In the other two strata, coarse silt is the second most abundant fraction. Thin section grain size analysis on samples from the Delta Sandstone and the sandy part of the third cycle of the Battle River Interval (Figure 12) yielded means of 0.185 mm and 0.145 mm, respectively. The sandier sediment of the study area can, therefore, be classified as very immature, moderately sorted, fine-grained lithic sandstone according to the scheme of Chen (1968).

Mineralogy of sandstone samples from the Delta Sandstone and from beds in the Battle River Interval was determined by thin section analysis. The essential components of sandstone in the Battle River Interval and Delta Sandstone are plutonic quartz (35%), polycrystalline quartz (5%), chert rock fragments (25%), volcanic and sedimentary rock fragments (20%), and feldspar (15%). The volcanic rock fragments in these sandstone beds are very fine-grained and highly altered, making recognition of feldspathic laths within the fragments very difficult. For these reasons, differentiation between volcanic and sedimentary rock fragments was difficult and separate percentages for the two types of fragments were not estimated. The varietal minerals in the sandstone beds include muscovite, biotite, hematite, zeolite, sericite, carbonate, and zircon. A bright yellowish-green, microgranular substance, which may be glauconite,

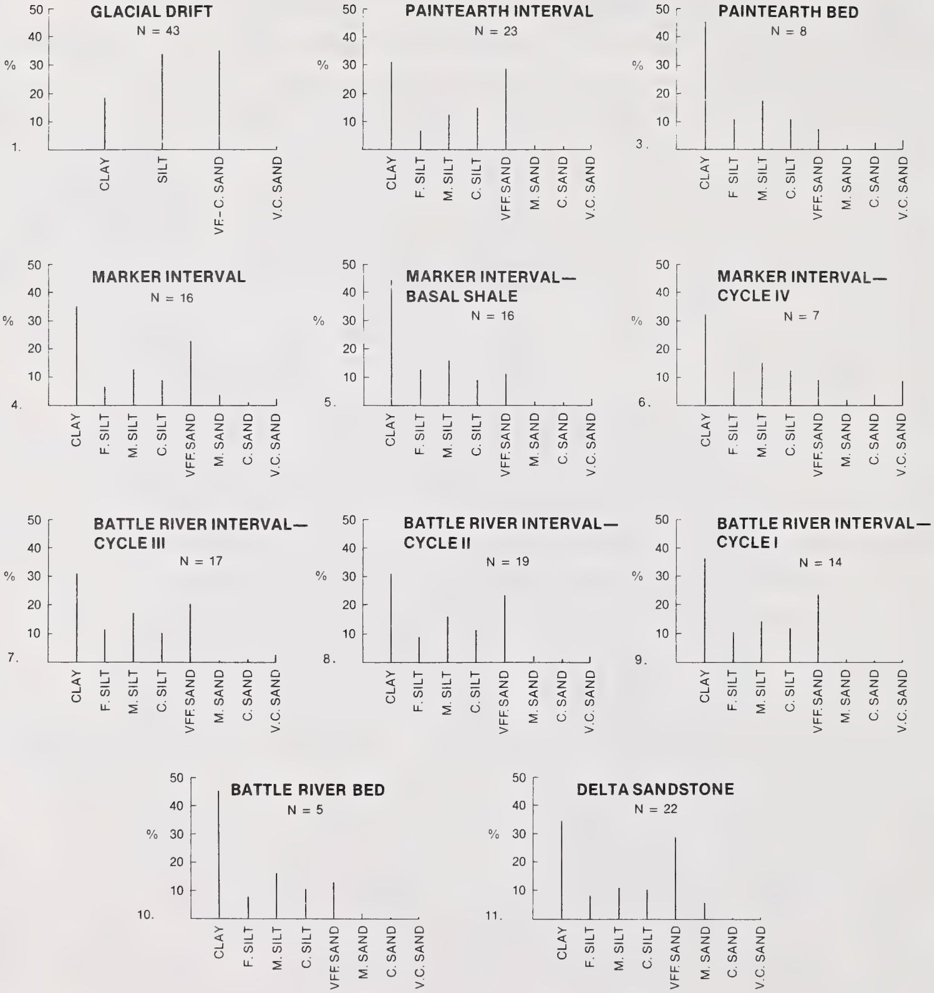


Figure 15. Mean grain size distribution of stratigraphic units in the Battle River study area.

was observed in thin section of sandstone of the Battle River Interval. The matrix of the sandstone units is primarily chert and clay. Where secondary silica production has been extensive, the sandstone is very well cemented.

The plutonic quartz in this sediment is generally unaltered and angular to sub-rounded. The chert fragments are angular to rounded; some fragments show intense pressure solution along their boundaries. Some chert fragments have a very high iron content and are associated with large amounts of interstitial hematite. Detrital grains of both potassic and plagioclase feldspar are generally highly altered, showing corroded grain boundaries and partial to total replacement by sericite and clay minerals (Figure 16). Several small grains of fresh, unaltered and unabraded plagioclase, however, were also observed. Abundant crystals of authigenic feldspar, probably adularia, growing on detrital grains and extending into the pore space were observed in the sandstone studied under the SEM (Figure 17a). Authigenic zeolite, in the form of radiating plates or accicular crystals, was also recognized (Figure 17b).

4.1.1 Clay Mineralogy

The clay mineralogy was determined by x-ray diffractometry using the standard Research Council process (Scafe, personal communication) and scanning electron and transmitted light microscopy (Maslowski Schutze, in press). Percentages of the mineral phases were estimated using the peak-height method; first order peaks from glycolated samples were measured. Chlorite was discriminated by heating to 575^{o}C.

Four primary clay mineral phases were identified within the Battle River samples. Smectite is the most abundant clay mineral phase in all eleven stratigraphic units. Illite, kaolinite, and chlorite are, in decreasing amounts, the other phases present (Figure 18). Smectite, illite and chlorite occur mainly as coatings on framework grains, but also commonly bridge pore space between grains, in which case the permeability is greatly reduced. The

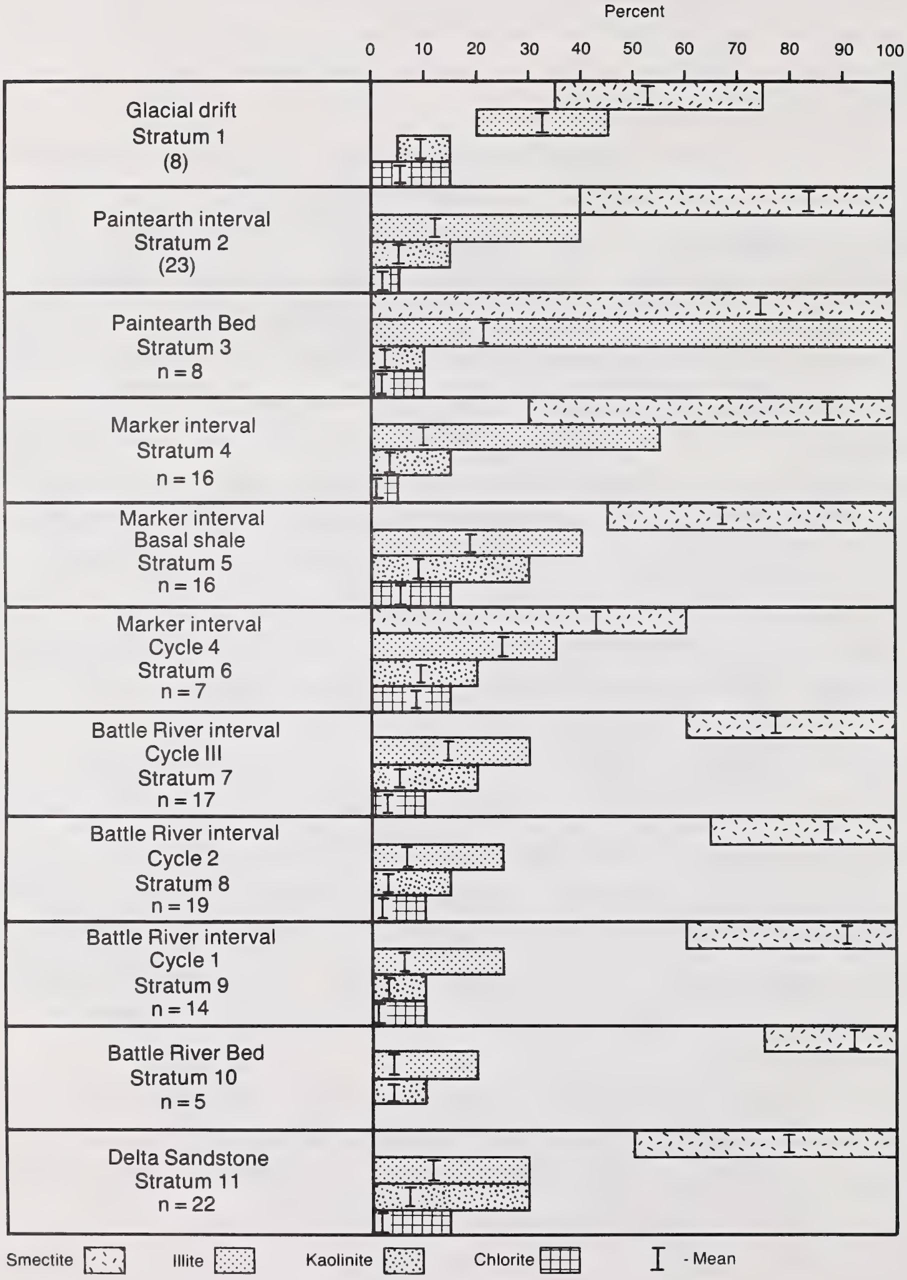


Figure 16. Percentages of clay mineral phases identified in the Horseshoe Canyon Formation and Glacial Drift in the Battle River study area

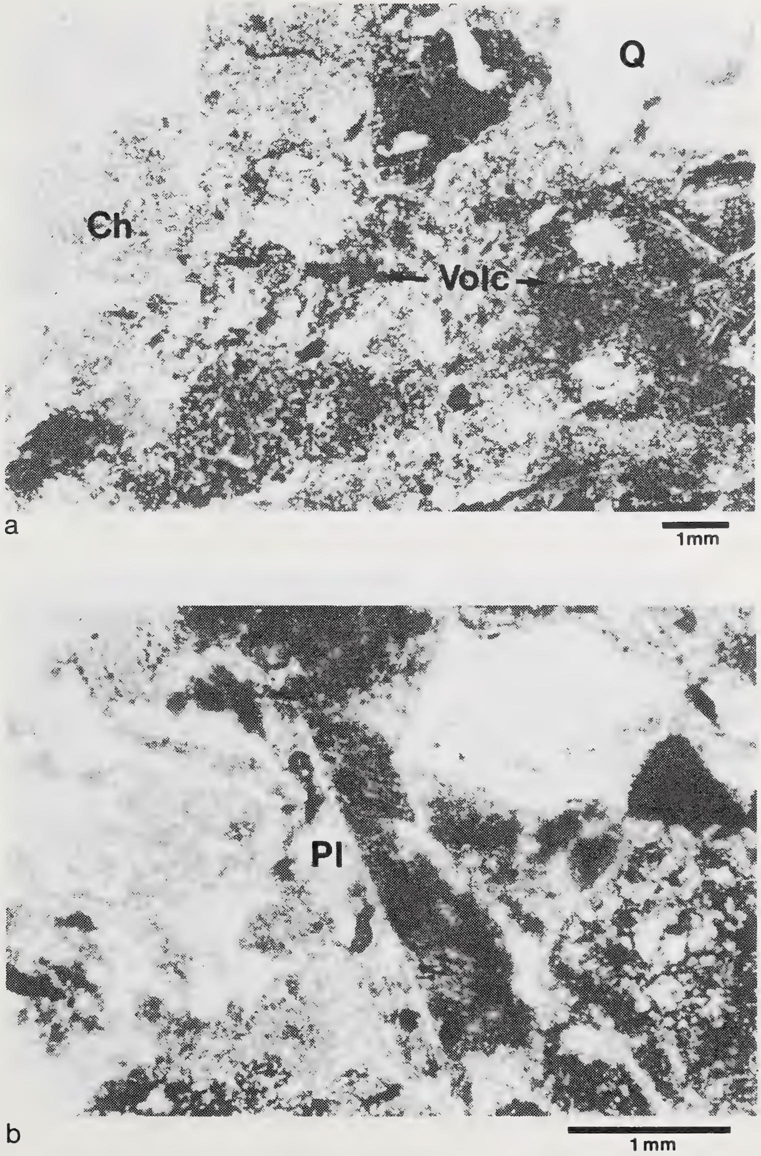


Figure 17. Photomicrographs of thin sections showing the mineralogy of sandstones in the Battle River study area. (a) Quartz (Q), chert (Ch) and volcanic rock fragments (Volc) in the Delta Sandstone (10x). (b) Highly altered twinned plagioclase with corroded grain boundaries from Cycle III - Battle River Interval (25x).

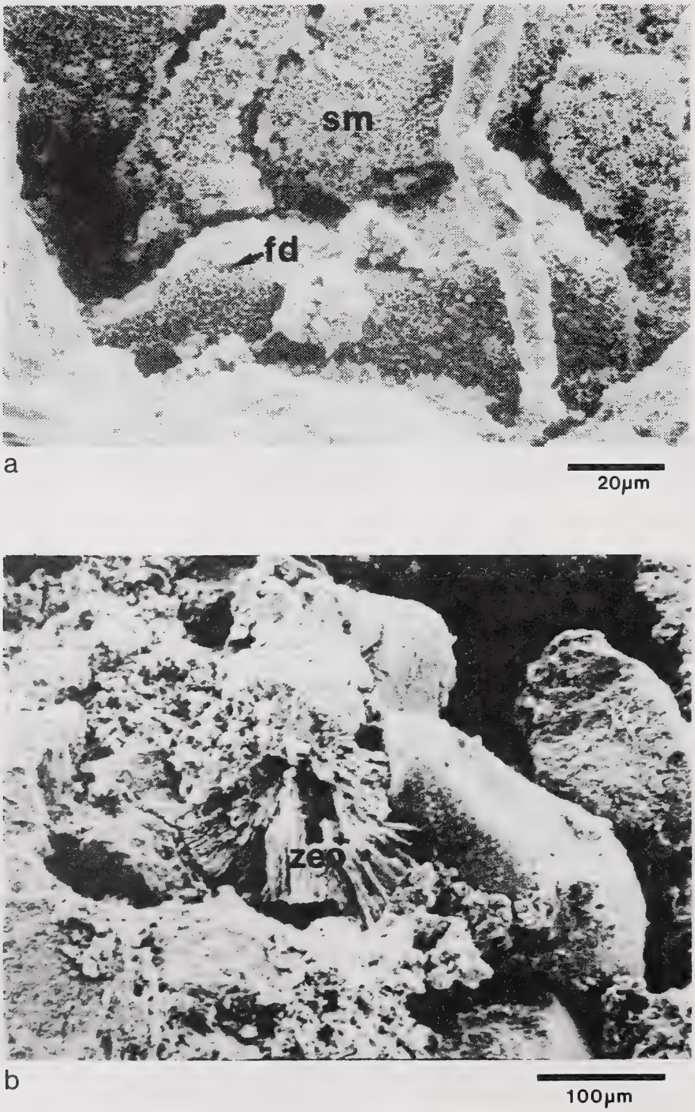


Figure 18. Scanning Electron Micrographs showing mineralogy of sandstone in the Battle River study area. (a) Flaky smectite (sm) forms clay coatings on detrital sand grains and authigenic feldspar (fd) extends into the pore space of the Delta Sandstone. (b) Radiating crystals of an authigenic zeolite mineral (zeo) in Cycle III of the Battle River Interval.

swelling properties of smectite result in reduced porosity, permeability and stability. Kaolinite occurs as randomly oriented clumps of booklets filling pore spaces (Figure 19); these booklets may become lodged in pore throats and thus decrease the permeability of the unit.

Kaolinite and illite appear to be more abundant (relative to smectite) in strata closely associated with coal-bearing horizons and in the glacial drift (Figure 20). The availability of water within the glacial drift and along aquifers results in chemical weathering of detrital and early authigenic minerals. Relatively high rates of flow in relation to dissolution along such permeable units has been cited as the cause of weathering of feldspars and the formation of kaolinite in other areas (Berner 1971). The higher smectite content of all the stratigraphic units in the study area is a reflection of the dry climate and low flushing rate, which allow decomposition of only the more reactive rock components, such as volcanic glass (Berner 1971).

Significantly higher percentages of chlorite are present in the glacial drift, the lower part of the Marker Interval and cycles II to III of the Battle River Interval (Figure 18). The higher percentages of chlorite within the Marker and Battle River Intervals may be a result of diagenesis of volcanic detritus deposited within brackish to marine waters.

The smectite-rich clay assemblages and the high percentage of matrix in the sediment of the lower Horseshoe Canyon Formation suggest that this sediment was deposited from water highly charged with volcanic detritus. It is likely that rivers were transporting large amounts of volcanic material in suspension and as bedload, and that air-fall deposition was concurrently adding yet more ash to the system. Subsequent diagenesis of the sediment has produced extremely bentonitic clastic rocks with very high matrix to framework ratios and very low permeability.

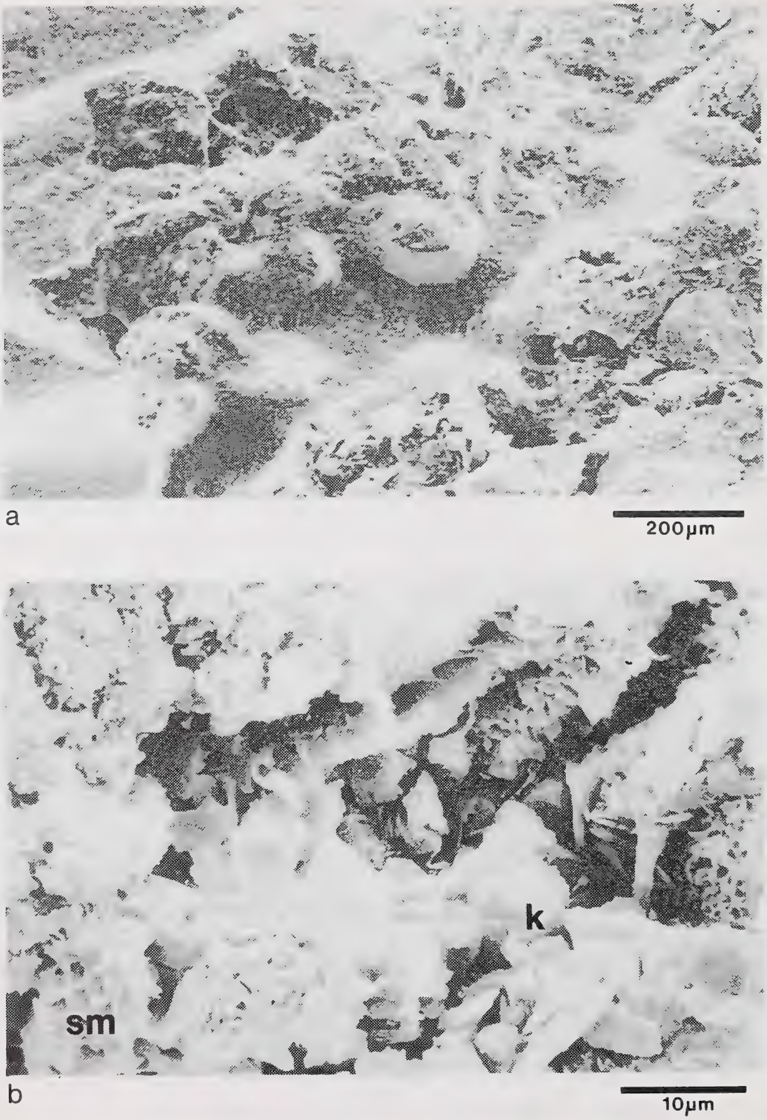


Figure 19. Scanning Electron Micrographs showing texture of sandstones in the Battle River study area. (a) Detrital grains draped with abundant clay minerals in sandstone of Cycle III - Battle River Interval. (b) Large crenulated flakes of smectite (sm) coat detrital grains and booklets of kaolinite (k) fill pore spaces in sandstones of Cycle III - Battle River Interval.

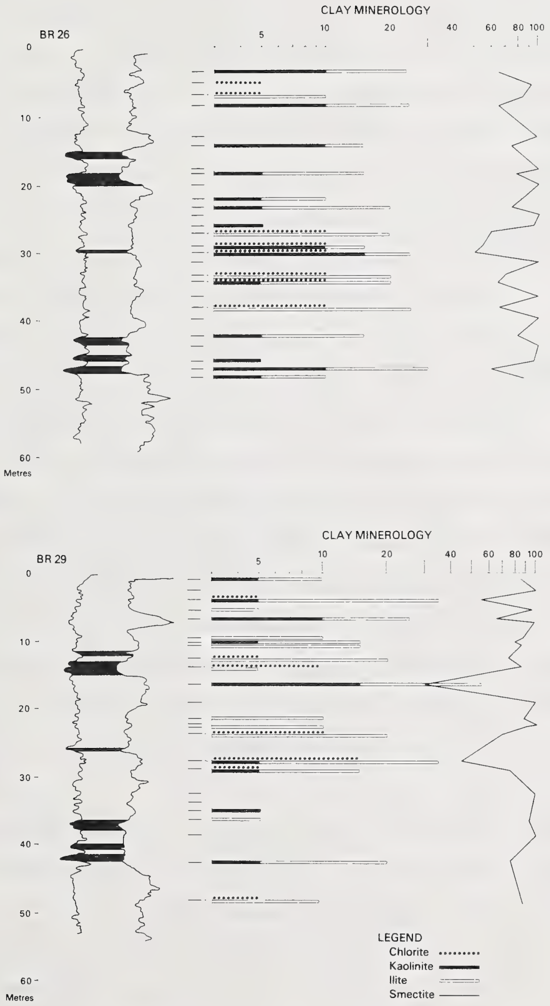


Figure 20. Distribution of clay minerals in coreholes 26 and 29 in the Battle River study area.

4.1.2 Sulfur in Overburden and Coal

Many of the chemical problems associated with mining and reclamation of coal are caused by sulfur present in the coal and overburden. The amount of sulfur present and its reactivity, which depends on its form of occurrence (whether in organic compounds or inorganic minerals) and the mineralogical habit in which it occurs (whether crystalline or amorphous), determine the type and magnitude of the problem posed by sulfur in coal and overburden sediments. The hydrological setting of the mining area is an additional important factor influencing the nature of the problem posed by sulfur. The most reactive, and therefore the most troublesome, type of sulfur is the mineral in the form of pyrite (FeS_2). However, not all pyrite is equally reactive. Work by Carrucio and others has demonstrated that even small amounts of very finely divided amorphous, "framboidal" pyrite produces much more significant acid spoil and acid mine drainage problems than much larger quantities of well-crystallized euhedral pyrite (Caruccio 1975; Caruccio et al. 1977, 1980; Caruccio and Geidel 1978; Geidel 1979). Although not generally as reactive as fromboidal pyrite, some organic, sulfur-bearing compounds are more reactive than well-crystallized euhedral pyrite and can produce significant amounts of sulfur upon weathering (Cameron et al. 1980). Under conditions of dominantly downward moving water where leaching is strong, weathering of reactive pyrite tends to produce low pH, acidic spoil and acid mine drainage. Such is the case in the Appalachian region of the United States, in most of the coal fields of western Europe, and in isolated locations in western North America. Under conditions of moisture deficiency, in which evapotranspiration exceeds precipitation, net water movement is upward and very little leaching is possible. Weathering of sulfur in this setting tends to produce high salinity but neutral to basic groundwater and surface water because of the large buffering capacity of soils and overburden caused by the abundance of base saturated phylosilicate minerals, carbonate minerals and free base-metal ions.

This type of setting is typical of most of the prairie regions of western Canada and the United States.

Because of the importance of sulfur in determining the nature and degree of chemical problems encountered in reclamation, one of the first research priorities of the RRTAC Plains Coal Reclamation Research Program was to identify the abundance and form of occurrence of sulfur in overburden in plains coal mines of Alberta. On the basis of operational experience in plains coal mines and electrical generating stations prior to the outset of research in the late 1970s no significant problem with sulfur was anticipated. Work by the Kananaskis Centre for Environmental Research demonstrated that the total sulfur content of overburden in the Battle River mining area was, in fact, low (Cameron et al. 1980). It was further demonstrated that the sulfur was present largely in an organic form with relative low reactivity (Cameron et al. 1980).

Two types of study were initiated by the Plains Hydrology and Reclamation Project to evaluate the presence and significance of sulfur in the overburden. The first was the geological and mineralogical studies reported here; the second was a series of experiments to evaluate the processes of weathering and the products generated by weathering the overburden. Results of the PHRP studies are consistant with earlier work. Pyrite and sulfur content of the overburden and coal are generally low, and the sulfur is generally not very reactive.

Sedimentological studies discussed elsewhere in this report establish that the overburden sediment was deposited largely in a continental environment immediately adjacent to the ocean. Studies of modern environments and in coal-bearing sequences elsewhere (Caruccio et al. 1977; Horne et al. 1978) strongly indicate that sulfur content and especially pyrite content is low in such settings. The only report of elevated sulfur levels from coal in the Battle River mining area is from isolated samples from the Battle River Bed near the south end of Paintearth Mine (Merv Rogen, Luscar Ltd., Personal Communication 1985). In this area, the Battle River Bed thins and splits into numerous thin beds.

Marine fossils have been collected from partings in the Battle River Bed near this area as discussed above (p. 12). These facts taken together, suggest that marine conditions can be expected in isolated locations in the lower part of the Battle River Bed, especially in the southeastern part of the coal field, and that in these areas the sulfur level may be significantly higher than elsewhere in the field.

In addition to the evidence of marine conditions for deposition of some partings in the Battle River Bed, higher than typical levels of sulfur in certain beds in the Battle River Interval and just above the Marker Bed are indicated by data on sulfate ion content of saturation-paste extracts (Figure 21). The interpretation of additional returns to marine conditions both below and above the Marker Bed is also supported by micropaleontological evidence that is discussed above (p. 16), and is given further credance by the presence of pyrite in these same beds. The presence of pyrite has been inferred from a series of iron oxidation rings that were found in core samples from wells 6, 24, 26, and 29 (Figures 12 and 22).

In well 24, 26, and 29, the oxidation rings are restricted to strata closely overlying or underlying the Marker Bed. In well 6, however, the rings occur throughout the Battle River and Marker Intervals. All occurrences of the oxidation rings were found in shale or silty shale. The centre of each oxidation ring is occupied by a small (2 to 3 mm) black carbonaceous fragment. In one sample from well 29 (25.9 m), small translucent prismatic crystals of gypsum, approximately 0.4 mm long, were observed along the edge of the carbonaceous fragment. A reddish-brown halo is developed in all directions away from the carbonaceous fragment for a distance of as much as 1 cm in these oxidation rings. Thin powdery crusts of an unidentified yellow mineral occur within some of the rings. One microcrystalline cube of pyrite was observed in core from well 29. It is likely that authigenic microcrystalline pyrite formed in these

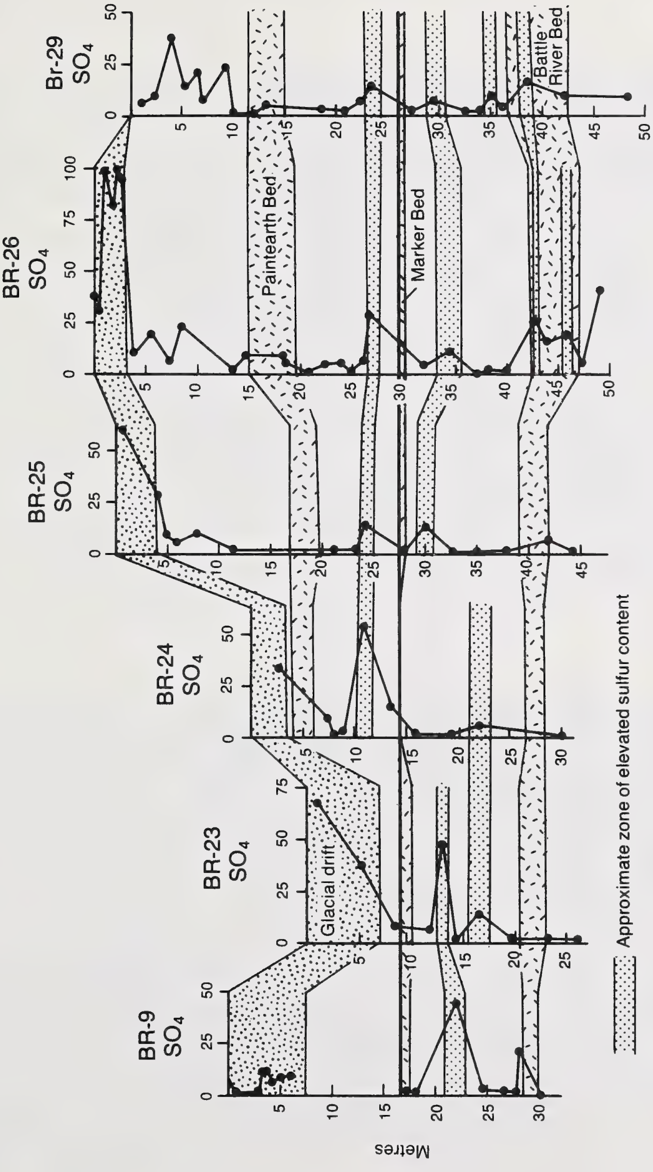


Figure 21. Sulfate concentration anomalies in satuation-paste extracts from beds in the Battle River and Marker Intervals are interpreted to reflect marine depositional conditions. Sulfate content is expressed as meq/L.

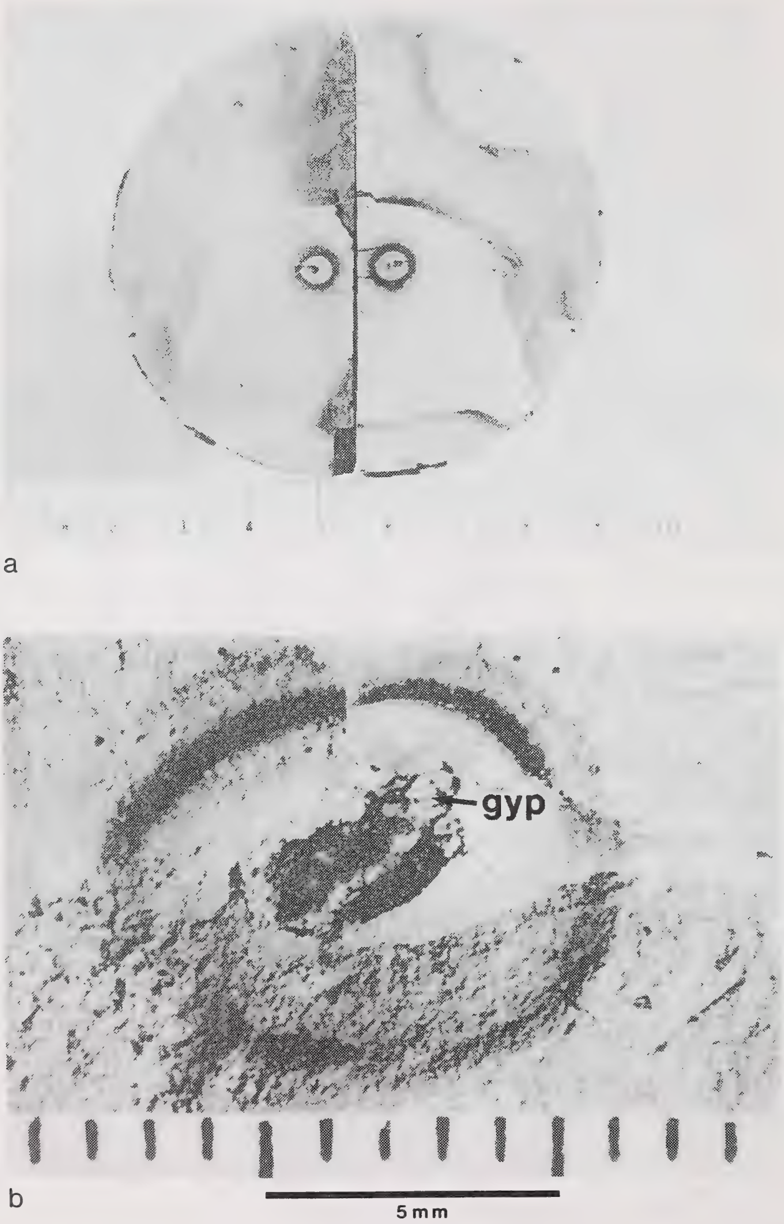


Figure 22. Iron oxidation rings in shale of the Battle River Interval. The dark centre of each ring is a carbonaceous fragment. Needles of gypsum (gyp) are observed in some oxidation rings.

sediments and has since been oxidized to produce the rings now observed.

Studies of isotopic ratios of sulfur in overburden samples further comfirm the sedimentological interpretations of the depositional environment of the overburden. The $w^{34}S$ content of the lower part of the overburden in coreholes 5, 6, 10, 23, and 24 ranges between +5 and +20 (Figure 23). Values in this range are typical of shallow marine or brackish environments that are closed to H_2S (that is the supply of metal ions available to form sulfide minerals was limited relative to the abundance of H_2S or the formation of sulfate minerals was delayed) (Ohmoto and Rye 1979).

The sulfur isotope data have also been interpreted to indicate two events of oxidation and reduction in the stratigraphic column studied at Battle River. The heaviest isotopes in these strata occur in the lower portion of the coreholes where $w^{34}S$ values are as high as +20 per mille (Figure 24). Above and below the Battle River Bed, $w^{34}S$ values drop to within the 0 to +5 per mille range. This group of data is thought to reflect oxidation resulting from a lowering of the water table level, likely during the mid-Holocene. Upon subsequent rising of the water table, fractionation of the sulfur isotopes occurred and the newly reduced sulfur was enriched in the lighter isotope due to the kinetic effect.

Coreholes 6, 23, and 24 show a second oxidation and reduction event in the vicinity of the Marker Bed (Figure 24). At this level $w^{34}S$ values are reduced to -12, -23, and -7 per mille in the three coreholes. Oxidation-reduction at this level is most probably related to a shift in position of the modern water table, which resulted in a second event of isotope fractionation.

In coreholes 5 and 6, $w^{34}S$ values near the surface are near 0 per mille, whereas in coreholes 10, 23, and 24, values are near -10 per mille. Wells 5 and 6 are situated topographically lower than the other three wells. Therefore, the sediments at sites 5 and 6 may have remained saturated and escaped a second oxidation-reduction cycle.

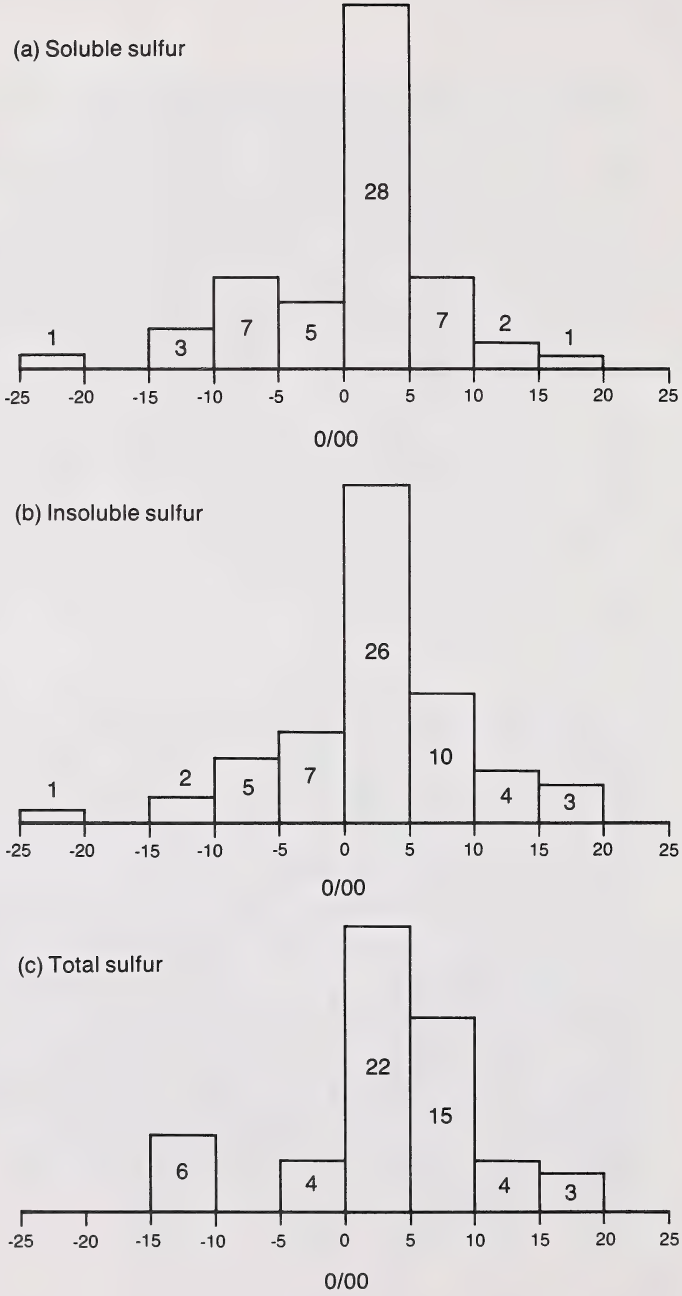


Figure 23. Histograms of $\delta^{34}S$ of (a) soluble sulfur, (b) insoluble sulfur, and (c) total sulfur in samples from the Battle River study area.

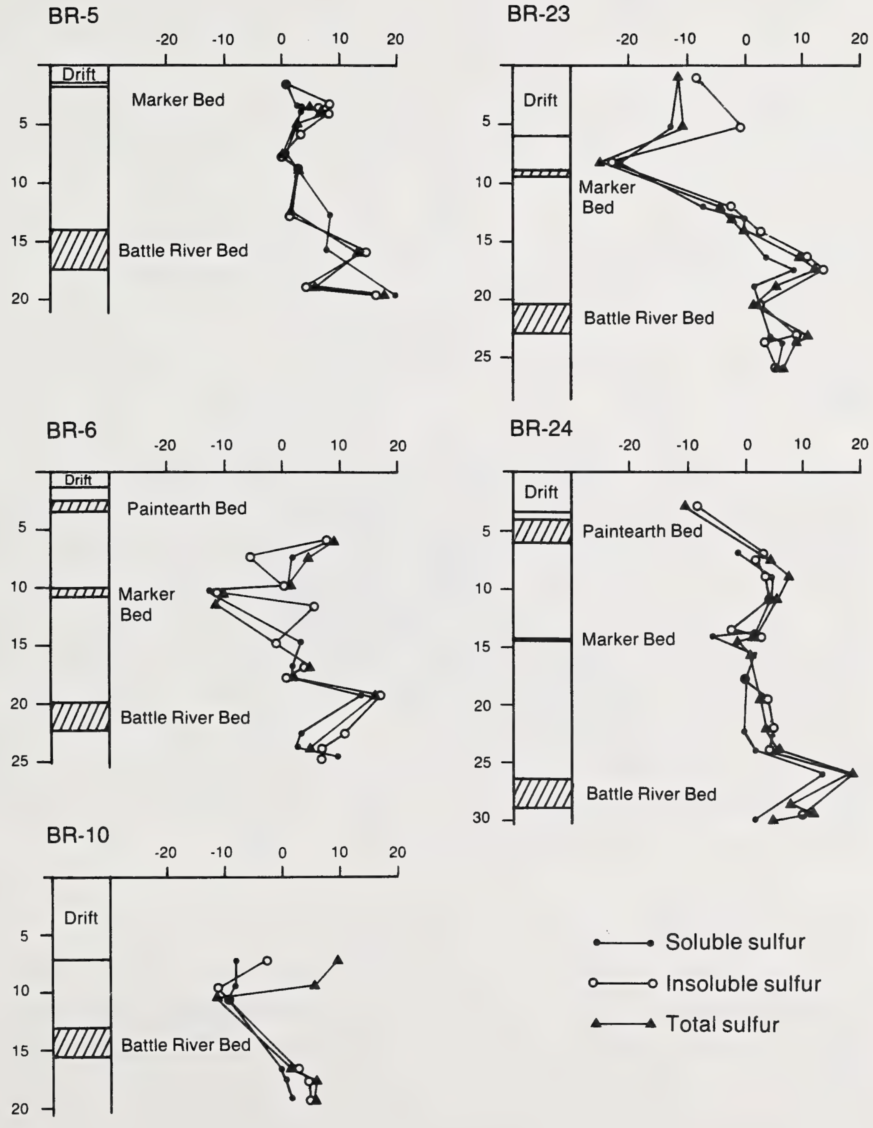


Figure 24. Relationship of isotopic composition of sulfur (δ^{34}S %o) in sediment to depth in testholes 5, 6, 10, 23, and 24 in the Battle River study area.

4.2 SEDIMENTOLOGY

In order to evaluate the potential to use selective mining and material handling techniques to prevent or control long-term salinization of reclaimed land, it is first necessary to describe the distribution of various bodies of sediment in the overburden. It has been shown in studies elsewhere in North America that deleterious material can occur only in isolated zones in the overburden of some mine sites (Dollhopf et al. 1981). As discussed above, it has been further demonstrated that the distribution of elements such as sulfur and some trace elements is a function of the depositional environment of the rocks (Horne et al. 1978). Specifically, sulfur content is highest in rocks deposited from marine and brackish water (Horne et al. 1978).

In order to define the distribution of sediment bodies, and as an aid to environmental interpretation, the overburden above the Battle River Bed was divided into a series of 1.5 m slices beginning at the top of the Battle River Bed. The relative proportion of sand, silt, and clay in each interval was interpreted from geophysical logs. Thirteen lithofacies maps were generated from which the paleogeography was interpreted. Data are sparse or lacking for overburden above the Battle River Bed in the NE and SW corners of the study area, and much of the overburden above the Paintearth Bed has been eroded from the entire area. This distribution of data points was considered in the interpretation of the maps.

4.2.1 Distribution of Sedimentary Deposits

Linear, northwesterly trending sand bodies were recognized in the northwest corner of the study area throughout the series of maps. Slice Map BR-2 (Figure 25) exemplifies the distribution pattern of silt and sand within the Battle River Interval. During this interval, deposition of sand was concentrated along the west and south boundaries of the study area. Sand splays episodically extended into the central portion of the area where mud was, otherwise, the primary deposit. Slice Map BR-8 (Figure 26) shows

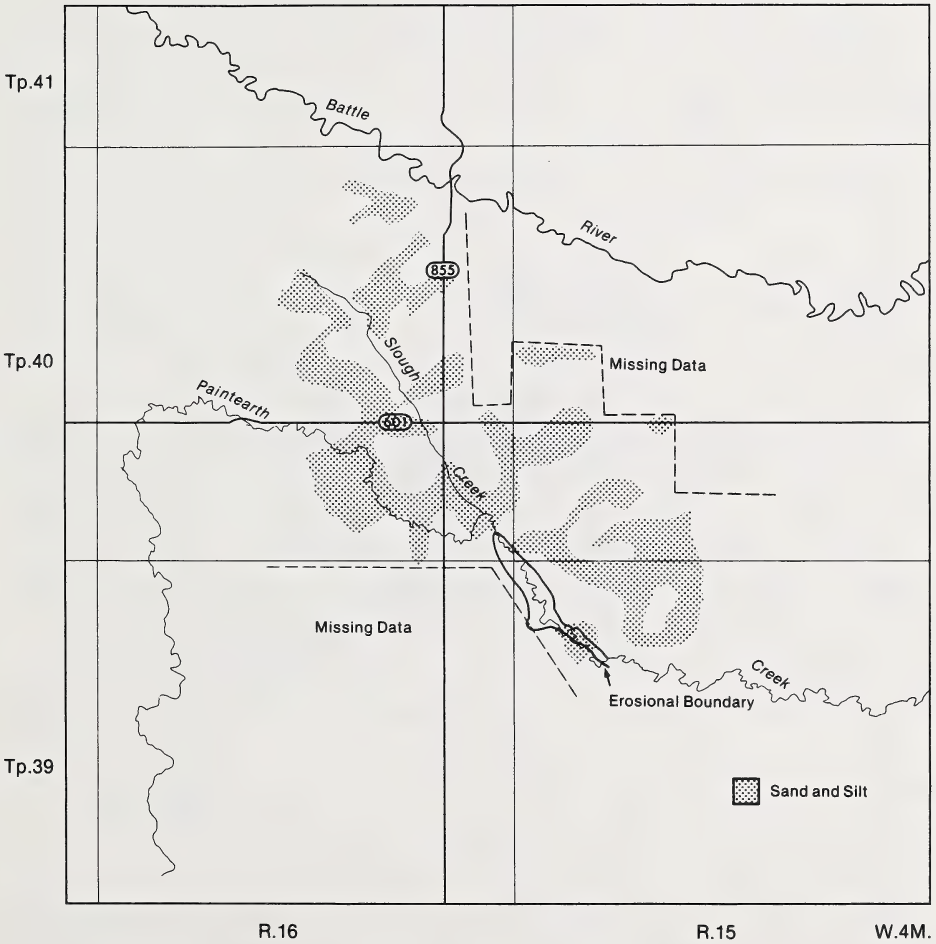


Figure 25. Map showing typical distribution of sand in the lower part of the Battle River Interval in the central part of the Battle River study area.

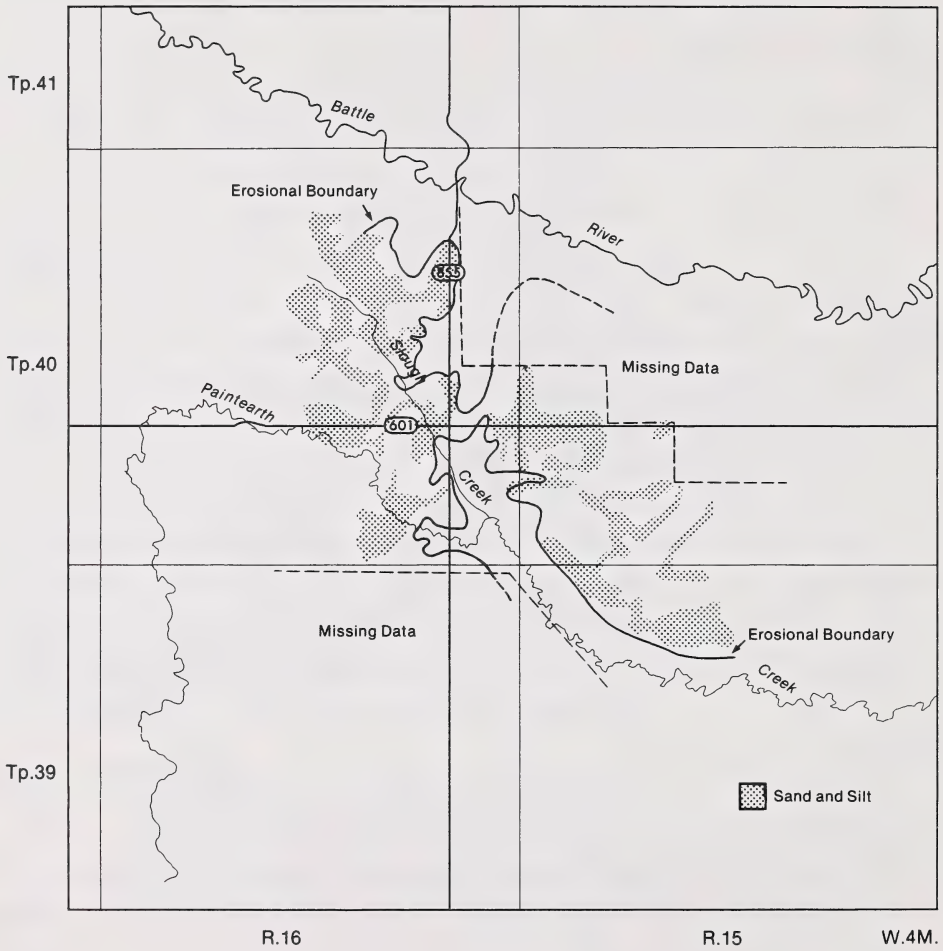


Figure 26. Map showing typical distribution of sand in the upper part of the Battle River Interval in the central part of the Battle River study area.

that shortly before deposition of the Marker Bed, numerous irregular, elongate bodies of sand were deposited in the study area. Slice maps through the lower part of the Marker Interval show increased mud deposition. Near the top of the Marker Interval, sand deposition was restricted to the northwest and southeast corners of the study area (Figure 27). In the central portion of the study area organic mud was being deposited; this mud grades upward and westward into the carbonaceous deposits of the Paintearth Bed. During the initial stages of deposition of the Paintearth Interval, small tongues of sand were brought into the study area from the west and an extensive sheet of sand continued to be deposited in the southeast corner of the study area.

4.2.2 Depositional Setting of Rocks of the Horseshoe Canyon Formation

4.2.2.1 Previous work. An excellent review of previous work on interpretation of the depositional setting of the upper part of the Bearpaw Formation and the lower part of the Horseshoe Canyon Formation has recently been published by Hughes (1984). The following discussion is taken, nearly verbatum from Hughes' work.

"Interpretation of the depositional setting of transitional strata between the Bearpaw and lower part of the Horseshoe Canyon Formations has been addressed in varying degrees of detail by several authors. Given and Wall (1971) examined microfauna-microflora and paleoecological relationships within the Bearpaw Formation in surface and subsurface sections in south-central Alberta. Havard (1971); Wall et al. (1971); Hills and Levinson (1975); and Wall (1976) examined lithologic, microflora-microfauna, and paleoecological relationships within the Bearpaw Formation and lower Horseshoe Canyon Formations in core from a well drilled near Strathmore, about 30 km east of Calgary" (Figure 3). "Habib (1981) examined lithologic relationships within the Bearpaw Formation in the subsurface of the Calgary-Drumheller area, using oil and gas well data. Regional

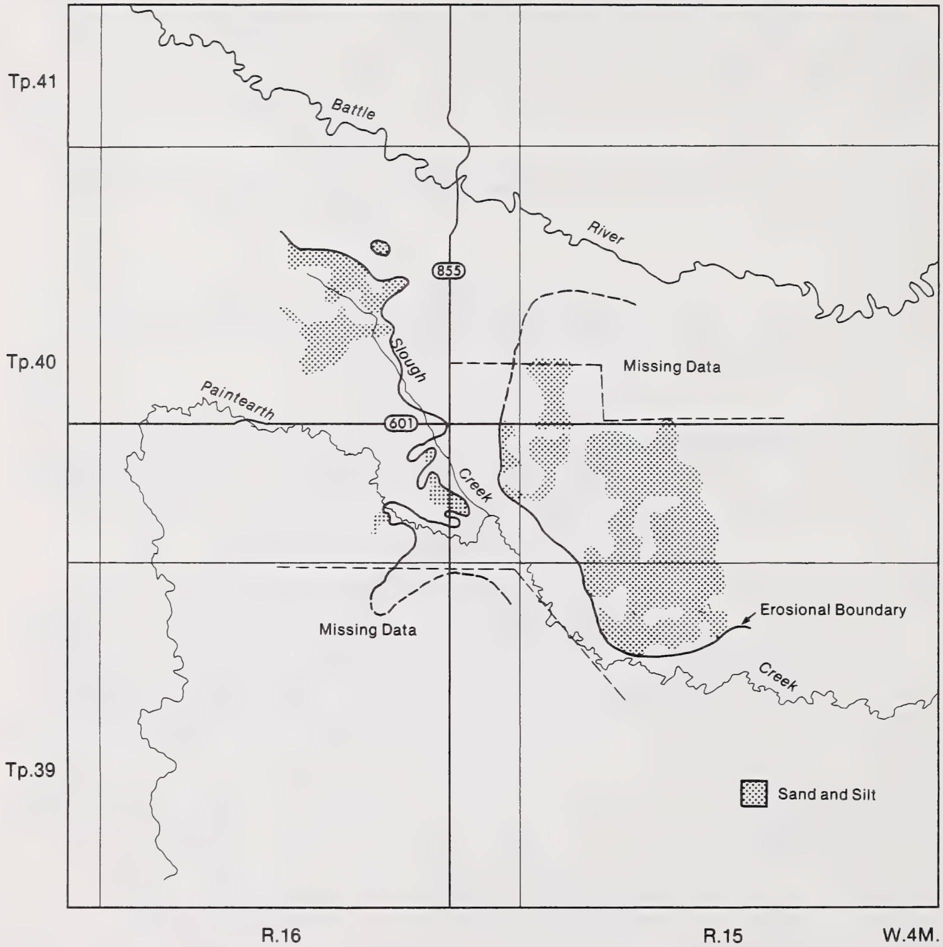


Figure 27. Map showing typical distribution of sand in the upper part of the Marker Interval in the central part of the Battle River study area.

studies of the Edmonton Group, some of which contain brief discussions of depositional environments, include those of Elliott (1960); Ower (1960); Williams and Burk (1964); Irish and Havard (1968); and Irish (1970).

"Several detailed studies of lithologic and sedimentological relationships in transitional Bearpaw-Horseshoe Canyon strata have been based on examinations of excellent surface exposures along Red Deer River near Drumheller. These include studies by Allan and Sanderson (1945); Shepheard (1969); Shepheard and Hills (1970); Gibson (1977); and Rahmani (1981, 1982). The major conclusions of these workers, as they relate to the depositional setting of the Dodds-Round Hill coalfield, are outlined briefly below.

4.2.2.1.1 Bearpaw Formation. "The Bearpaw Formation can be traced in surface exposures from southern Alberta to the Athabasca River, northwest of Edmonton, where it pinches out within nonmarine sediments of the Wapiti Group" (Figure 3). "Regional subsurface studies indicate the Bearpaw Formation pinches out to the west in the subsurface along a north-trending line located approximately 100 km west of Edmonton and 30 km west of Calgary (Williams and Burk 1964). North of Edmonton, Williams and Burk (op. cit.) suggested this pinch-out line curves to the northeast to intersect the present land surface near the Athabasca River (see Wall et al. 1971, their Figure 1).

"In Dodds-Round Hill area, the Bearpaw Formation is about 60 m thick. At Castor, about 100 km farther southeast, it is 140 m thick (Given and Wall 1971). In the subsurface at Strathmore Wall et al. (1971) included 27 m of strata within the Bearpaw Formation, which there is overlain by a transition zone 80 m thick. Habib (1981, his Figure 20) reported 140 m of Bearpaw strata at Strathmore and over 100 m northwest of Calgary, which suggests he may have included strata belonging to the transition zone of Wall et al. (1971) in his definition of the Bearpaw Formation.

"Most workers recognize a series of gradational coarsening-upward cycles within the Bearpaw Formation. These cycles grade upward from shale through interbedded siltstone and shale to sandstone, in some cases with minor carbonaceous interbeds. Microfauna-microflora associations suggest that the shaly parts of these cycles accumulated in shallow, brackish or marine environments. Overlying sandstone and minor carbonaceous beds may represent a shallow brackish water habitat or, in some cases, subaerial exposure. Given and Wall (1971, p. 52) concluded that although several episodes of deepening are represented, all of the Bearpaw sediments they examined in south-central Alberta were deposited in '...quite shallow water...'. Wall et al. (1971, p.697) suggested '...a shallow, inner-neritic environment with average water depth probably under 20 ft...' for Bearpaw sediments in the Strathmore core. Habib (1981) related these transgressive-regressive sequences to the successive, eastward progradation of deltaic complexes across the area.

"The orientation of the western shoreline of the Bearpaw Sea is important in determining the regional paleoslope direction, and hence the progradation direction of the distributaries that deposited much of the sediment within the Bearpaw Formation. Williams and Burk (1964) indicate a north-south orientation of this shoreline south of Edmonton, and a northeast orientation farther north. Williams and Stelck (1975, p. 17) show an embayment in southeastern Alberta with an east-trending, northern shoreline on their paleogeographic map of early Maestrichtian time, which was somewhat later than the maximum extent of the Bearpaw Sea in the Late Campanian.

"The absence, due to erosion, of Bearpaw strata in east-central and northeastern Alberta makes the orientation of the western limit of the Bearpaw Sea north of Edmonton impossible to establish. However, given the present distribution of Bearpaw strata in the subsurface, the orientation of the shoreline south of Edmonton appears to have been roughly north-south.

4.2.2.1.2 Transitional Bearpaw-Horseshoe Canyon strata. "In the subsurface near Strathmore, transitional Bearpaw-Horseshoe Canyon strata display two prominent coarsening-upward sequences, overlain by coal-bearing strata of the Horseshoe Canyon Formation. A 1.5 m thick coal bed occurs at the base of the transitional interval at this locality (Wall et al. 1971). Microflora-microfauna relationships suggest an alternating sequence of transgressive marine and regressive brackish to freshwater environments, with the youngest marine phase represented by shales at the base of the uppermost coarsening-upward sequence (Wall et al. 1971).

"Depositional models developed from examination of the surface exposures along Red Deer River near Drumheller (Allan and Sanderson 1945; Shepheard and Hills 1970; Gibson 1977; Rahmani 1981, 1982) generally agree on the following points:

1. The transitional strata are the result of sedimentation within fluvial-deltaic complexes along the western margin of the Bearpaw Sea.
2. Although marine or brackish strata recur above the lowermost coal seams in the Horseshoe Canyon Formation, there is an overall upward progression from predominantly brackish or marine to freshwater fluvial environments.

These authors differ, however, in their interpretations of the overall morphology and depositional subenvironments within these delta systems, and on their direction of progradation. As the succession along Red Deer River near Drumheller is laterally equivalent and lithologically similar to the succession in the Dodds-Round Hill coalfield" (and the Battle River coal field), "it is instructive to consider each of these previous studies in more detail".

"Allan and Sanderson (1945) studied the entire Edmonton Group, utilizing exposures along Red Deer River between Red Deer and East Coulee" (Figure 3). "They estimated the overall lithologic composition of the group as 30% clay, 50% silt, and 10 to 15% sand, with a slight predominance of silts and clays in the lower part of the group. They also identified two varieties of concretionary units: Calcite cemented units associated with coarse grained lithologies and sideritic, clay-ironstone units associated with the finest grained lithologies. In some cases, concretions with a sand matrix had dinosaur bones or wood fragments within their cores, which they interpreted as evidence of subaerial exposure. They suggested that the transitional deposits of the lower Edmonton Group were deposited in delta systems of low relief (op. cit. p. 74), within which occurred channel, swamp and floodplain subenvironments. Although they suggested the source area for clastics in the Edmonton Group was to the west, they did not specify the progradation direction of these delta systems.

"Shepheard and Hills (1970) studied 32 stratigraphic sections covering an interval of about 120 m of transitional Bearpaw-Horseshoe Canyon strata, measured along Red Deer River and Willow Creek near Drumheller" (Figure 3). "They interpreted the laterally extensive sandstone units, which gradationally or abruptly overlie interbedded siltstones and shales of the Bearpaw Formation, as mouth bar and channel deposits of major distributaries, prograding in easterly and northeasterly directions. Overlying these sandstone units, they recognized an interval containing marginal swamp, levee, and marsh subenvironments, represented by siltstones, shales and coal deposited adjacent to major distributaries in flood basin settings on a lower delta plain. Overlying this interval they recognized a succession of marginal marine subenvironments, including interdistributary bay-fill, beach, barrier, marsh, open and restricted bay, and mud flat. They attributed the upper most part of the succession to deposition by entirely nonmarine, fluvial processes on a lower delta plain. On the basis of limited paleocurrent data, the same writers suggested that the shoreline was oriented north-south during this period, with distributaries and fluvial channels prograding in an easterly and northeasterly direction. They also suggested that although these strata contain features that do not correspond with the deposits of any one modern delta system, they most closely resemble the deposits of the present Mississippi River Delta.

"Gibson (1977) studied the entire Edmonton Group, utilizing stratigraphic sections measured at 55 localities along Red Deer River and its tributaries between Ardley and East Coulee" (Figure 3). "He interpreted the laterally extensive sandstone units at the base of the Horseshoe Canyon Formation as the deposits of '...large and small braided streams flowing across a rapidly prograding delta...' (op. cit., p. 16). Overlying, thinner, laterally less extensive sandstone units were interpreted as the deposits of smaller braided channels. He suggested that interbedded siltstone, claystone and fine grained sandstone may represent possible crevasse splay, interdistributary bay and flood basin deposits. Oyster-bearing black shale and sandstone units in the lower part of the formation were attributed to deposition within shallow marine or brackish water lagoons, bays or salt marshes. Coal seams represented accumulations of vegetal material in flood basin marsh or swamp areas. Gibson (op. cit. p. 16, 17) suggested the delta of the present Brahmaputra River of Bangladesh as a possible modern analogue for the deposits of the transitional Bearpaw-Horseshoe Canyon interval. Although he did not suggest a progradation direction for these deltaic complexes, the mean orientation of 28 paleocurrent readings collected over the transitional Bearpaw-Horseshoe Canyon interval (Gibson, personal communications, 1983) is azimuth 087 degrees, suggesting paleoflow to the east with a north-south oriented shoreline.

"Rahmani (1981, 1982) conducted a detailed study of 28 stratigraphic sections measured along Red Deer River in the study areas of Shepheard and Hills (1970) and Gibson (1977). Rahmani interpreted the basal sandstone units as the products of deposition within a distributary channel-estuarine complex. Above these basal sandstones, he recognized swamp, tidal flat, tidal channel, beach, bay-lagoon, and barrier island subenvironments. At the top of the section, he recognized fluvial strata deposited "... in the upper to lower delta plain ..." (Rahmani 1982, p. 22). Although his interpretation of the section in terms of interbedded marine, nonmarine and brackish sediments deposited within a deltaic environment is similar to the interpretations of previous workers, Rahmani differs from them in his interpretation of paleoflow directions and of the energy regimes and morphology of the depositing delta systems. Paleocurrent data collected by Rahmani from the basal sandstone unit (his unit E1) show a mean orientation of about azimuth 050 degrees (op. cit., p. 8, his Figure 8), and data from the unit immediately overlying the basal sandstone (his unit E2) have a mean orientation of about azimuth 060 degrees (op. cit., p. 14, his Figure 11). Rahmani suggested that paleoflow during deposition of the basal sandstone was from north and northeast toward the south and southwest, in an opposite direction to his paleocurrent data, and that paleoflow in the overlying unit was from "... east-northeast to west-southwest ..." (op. cit., p. 21). To account for this apparent contradiction of the paleocurrent data, Rahmani suggested these units were deposited in a tidally-dominated delta system, and that the directional structures measured were produced during the flood phase of tides, when currents were directed in a landward direction, and that ebb phase structures were rarely if ever preserved. In order to account for the presence of macro- to meso-tidal regimes and the existence of apparently anomalous southwestward-directed paleoflow, Rahmani postulated the existence of a local embayment in the area. He concluded that regionally, the ancient shoreline had an orientation of west-southwest to east-northeast with regional transport to the southeast. Rahmani suggested the tidally-dominated delta of the present Ord River in western Australia as a modern analogue for transitional Bearpaw-Horseshoe Canyon strata.

4.2.2.1.3 Interpretations from the Dodds-Round Hill coalfield. "Criteria for the interpretation of depositional setting in the Dodds-Round Hill coalfield include:

1. The overall geometry of stratigraphic intervals and interrelationships with the geometries of adjacent intervals, as determined from isopach maps.
2. The lithologic composition of all or portions of stratigraphic intervals determined from the abundance of lithologic types.
3. Lateral interrelationships between lithologic units in terms of their geometry and distribution both within and between specific stratigraphic intervals, as determined from lithology-thickness and lithology-percent maps and cross-sections.
4. Vertical lithologic relationships within all or portions of stratigraphic intervals as determined from Markov analyses and geophysical logs.

"By comparing the above relationships with those observed in modern and ancient delta systems, an understanding of the depositional processes and overall morphology of the fluvial and deltaic systems within which these strata accumulated can be achieved.

"Systematic studies of modern delta systems (Fisk 1961; Allen 1965b; Wright and Coleman 1973; Wright, Coleman, and Erickson 1974; Coleman and Wright 1975; Galloway 1975; and numerous others) reveal that delta morphology is a result of the complex interaction between fluvial and marine processes. Variables affecting fluvial processes include type of sediment and the rate and annual variation in the discharge of distributaries which, in turn, are largely a function of climate, source rocks, and the size and geometry of the drainage basin. Variables affecting marine processes include tidal range, wavepower, longshore currents, and the tectonics and geometry of the depositional basin. The relative energies of fluvial, wave and tidal forces are of primary importance in the determination of delta morphology and hence the geometry and distribution of lithologic units within it. Galloway (1975) constructed a threefold delta classification scheme based on the relative contributions of fluvial, wave and tidal forces. Characteristics of modern deltas that represent end members of this classification scheme, as well as those in which more than one process dominated, are discussed by Galloway (op. cit.); Coleman and Wright (1975); and Coleman and Pryor (1980), among others.

"Several factors limit possible interpretations of transitional Bearpaw-Horseshoe Canyon strata:

1. The Bearpaw Formation accumulated in a shallow, epeiric sea under conditions ranging from shallow marine to brief periods of subaerial exposure. This suggests that wave energy would have been relatively unimportant in the delta-forming process, since high wave energies are associated with steep offshore slopes.
2. The source area for sediments within this succession was probably uplifted highlands, 150 km or more to the southwest, which were undergoing deformation at the commencement of the Laramide Orogeny. Contemporaneous volcanism associated with this deformation is indicated by the laterally extensive bentonitic shale and bentonite seams within these strata that may represent altered volcanic ash deposits. The size of the drainage basin for any one delta complex may have been relatively small compared to the drainage basins of major deltas such as that of the present Mississippi River.
3. The western limit of the Bearpaw Sea apparently lay along a north-south trending line extending from the Foothills area of southwestern Alberta to the Athabasca River northwest of Edmonton (see previous discussion), where Bearpaw and adjacent strata are truncated by the present erosion surface (Williams and Burk 1964; Wall et al. 1971). There is little evidence for major deflections of this western limit, such as the embayment postulated by Rahmani (1981, 1982), since Bearpaw sediments are known to extend at least as far

> west as the Pembina Oil Field (Williams and Burk 1964). Extreme tidal ranges, such as those postulated by Rahmani (op. cit.), are favoured if elongate embayments or estuaries oriented at a high angle to the shoreline are present. Lack of evidence for such embayments in the subsurface distribution of the Bearpaw Formation, coupled with the probable shallow, epeiric nature of the Bearpaw Sea, suggest that tidal forces were probably of relatively minor importance in the delta-forming process.

"These constraints and the vertical and lateral lithologic relationships observed in the Dodds-Round Hill coalfield, suggest that deposition by northeastward and eastward prograding, fluvially-dominated delta systems may be the most appropriate model. Strata above the Round Hill Coal Zone are considered to have been deposited within fluvial-alluvial plain settings. This interpretation is similar to that proposed by Shepheard and Hills (1970) for transitional strata in the Drumheller area. A northeastward and eastward progradation direction is consistent with the distribution and geometry of lithologic units in the Dodds-Round Hill coalfield and the paleocurrent data collected in the Drumheller area by Shepheard and Hills (1970); Rahmani (1981, 1982); and Gibson (personal communications 1983). Jerzykiewicz and McLean (1980) also reported northeasterly paleocurrent directions for the laterally equivalent Brazeau Formation in the western foothills of central Alberta, and Lerbekmo (1963) and McLean (1971) reported northeasterly paleoflow for the Judith River Formation of southern Alberta and Saskatchewan, which immediately underlies the Bearpaw Formation". (Hughes 1984, pp. 67-70).

4.2.2.2 Battle River study area. The environments of deposition envisioned for the sediments of the Battle River study area are schematically illustrated in (Figure 28). The Basal and Deep Sandstones are laterally continuous sheet sands that may be marine or

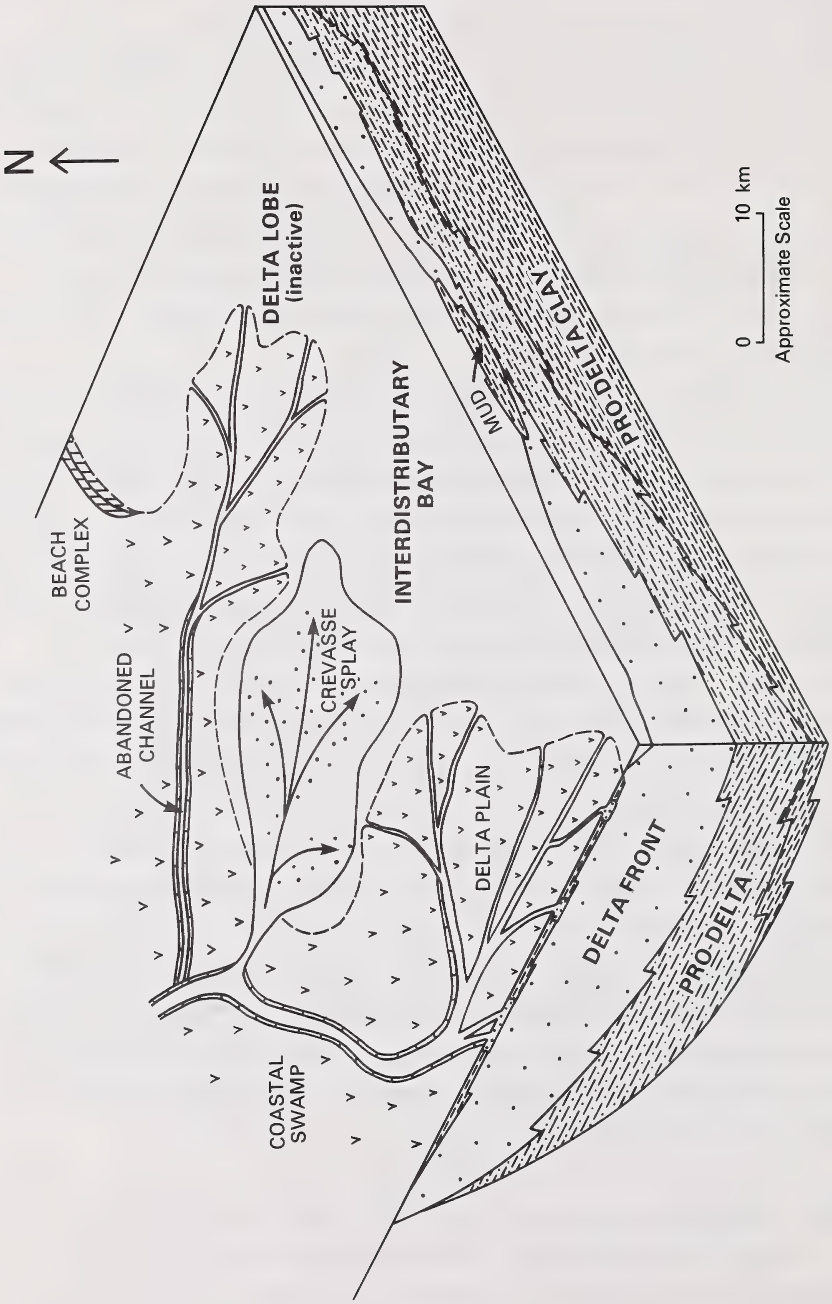


Figure 28. Generalized reconstruction of the environments of deposition of the lower Horseshoe Canyon Formation in the Battle River study area.

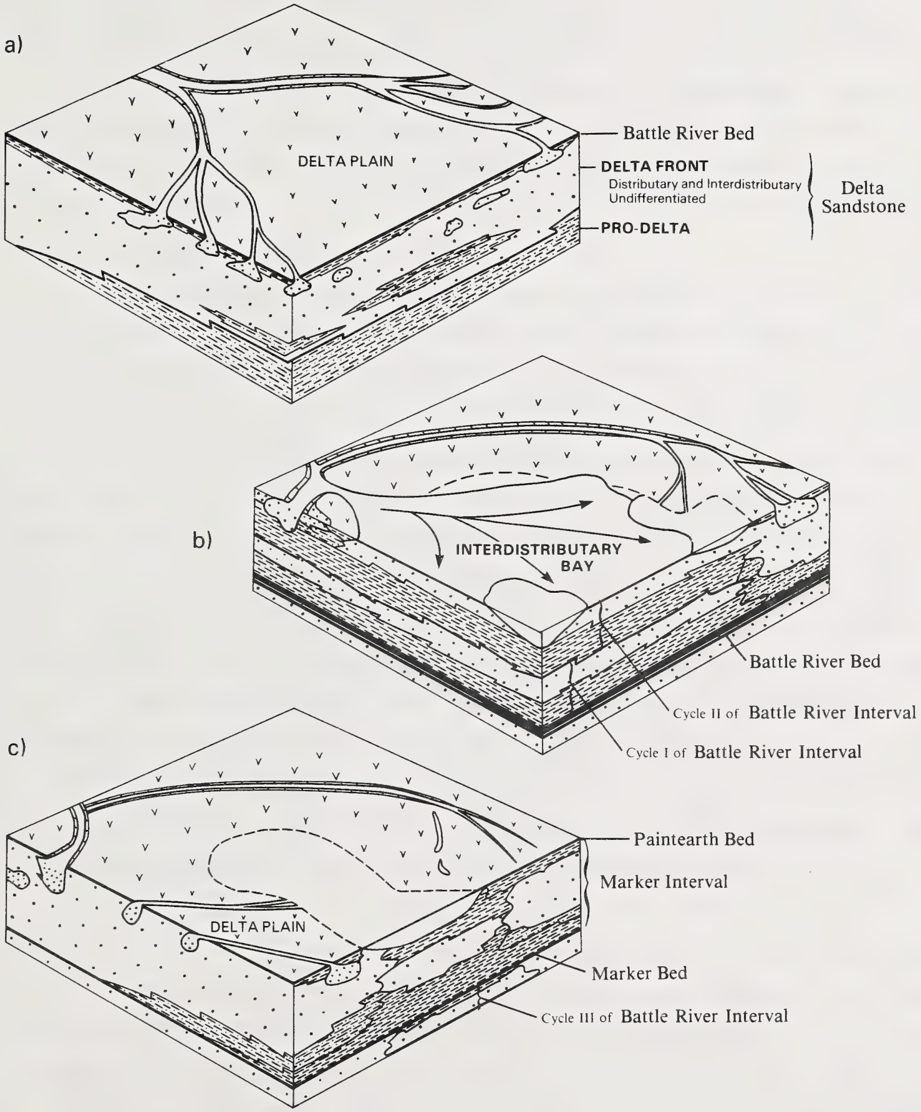


Figure 29. Reconstuction of depositional environments that formed the lower Horseshoe Canyon Formation in the Battle River study area. (a) Deltaic complex showing Delta Sandstone capped by Battle River Bed. (b) Interdistributary bay developed between deltaic lobes. Battle River Bed is overlain by coarsening upward cycles of Battle River Interval. (c) Filling in of bay and merging of deltaic lobes results in continuous marsh cover from which Paintearth Bed forms.

shoreline in origin, but because neither core nor outcrop data are available for these units, it is not possible to ascertain the environment of deposition. The Middle and Delta Sandstones are interpreted as early and established stages of a deltaic complex that prograded across the area from the northwest (Figure 29a). This directional interpretation is at odds with most of the regional interpretation discussed by Hughes (1984) above. Given the small size of the Battle River area, it is likely that a small embayment is involved, resulting in a local variation in flow direction. A very gradual relative rise in sea level then allowed accumulation of a very thick organic mat over the complex, which has since been transformed into 3 m of sub-bituminous coal of the Battle River Bed. The presence of oyster beds and elevated sulfur levels in the southern part of the area suggest the coal was formed in a brackish environment. Apparently the sea was quite close to the southern edge of the area during this period. Palynological studies indicate that, during the time interval between deposition of the Battle River and Paintearth coal beds, the study area was inundated by marine to brackish waters. The occurrence of iron oxidation rings within shale of the Battle River and Marker Intervals and the presence of glauconite within sand of these intervals further suggest that these units represent quiet, more reducing marine marginal environments where fine-grained organic sediment was deposited and remained unoxidized. The environment envisioned for the deposition of the Battle River and Marker Intervals is an interdistributary bay developed within a topographic low between two deltaic lobes. The three coarsening upward cycles identified in the Battle River Interval are interpreted as crevasse splay deposits that formed when the river intermittently broke through its levee and spilled coarse clastic sediment across the bay (Figure 29b). The merging of bay fill and deltaic lobes resulted in a continuous marsh cover over the area, recorded in the stratigraphic record by the Marker Bed. The brackish bay environment then returned and deposition of fine mud resumed, to be interrupted intermittently by innundations of silt and sand in the form of crevasse splays. The filling of the bay and sediment accumulation on the deltaic lobes gave rise to extensive coastal swamps that are now represented by the coal-bearing horizon of the Paintearth Bed (Figure 29c). A large bay continued to occupy the area throughout deposition of the Paintearth Interval. Lithofacies maps (Figure 26) suggest the locus of deltaic sedimentation had shifted further southeast by this time.

4.2.3 Summary

The strata related to Cretaceous coal deposits at the Battle River site encompass marginal marine and deltaic sediments of the upper Bearpaw and lowermost Horseshoe Canyon Formations. During Late Campanian time, repeated transgressions and regressions resulted in the intertonguing of marine shale and sheets of sand accumulated near shore. With time, a drop in sea level or an increase in sediment supply caused the progradation into the area of deltaic complexes, which were eventually capped by peat. Major distributaries developed to the north and south of the study area. Subsidence and lack of sediment resulted in an interdistributary bay, which was repeatedly filled by crevasse splay deposits. The Marker Bed and Paintearth Bed are products of coastal swamp development over the infilled bay and adjacent delta plains. The uppermost part of the stratigraphic sequence at Battle River reflects a continuation of deltaic and nearshore deposition through into mid-Maestrichtian time.

5. SURFICIAL GEOLOGY

5.1 BACKGROUND NARRATIVE

Following deposition of the rocks of the Lower Horseshoe Canyon Formation, the Battle River area was buried beneath an ever-thickening layer of sediment as rivers carried debris eastward out of the mountains. The sea was pushed farther to the southeast out of Alberta as the wedge of river sediment thickened and grew eastward. By the time this depositional cycle ended in the mid to late Tertiary, the Battle River area was buried by as much as 1 km of sediment (Nurkowski 1984, pp. 292-293). Once the mountains were lowered enough to no longer supply large volumes of sediment, the rivers began to remove the thick wedge of sediment burying east-central Alberta. By the onset of continental glaciation, perhaps one million years ago, most of the sedimentary wedge had been removed and the land surface was only slightly above its present position. The drainage consisted of a series of large northeastward draining rivers that were situated in broad deep valleys. The Battle River study area is situated on the south side of a major tributary valley to the ancestral Red Deer River. The area was likely rolling terrain without any deeply incised valleys. If any evidence of the modern Battle River and Paintearth Creek Valleys was present, it would have been in the form of insignificant tributary valleys.

Evidence elsewhere in Alberta (Fenton 1984), indicates that the Battle River area must have been glaciated numerous times during the Quaternary, although there is no record of most of this period preserved in the Battle River area. Evidence for two glacial events has been found in the Battle River area, but both are most likely related to the last glaciation to affect the area. It seems likely that modifications to the preglacial drainage in the area must have occurred during other glaciation prior to this. The only evidence available, however, indicates that the present Battle River and Paintearth Creek Valleys were formed during the final deglaciation of the area, perhaps as recently as 10 000 years ago.

5.2 SURFICIAL MATERIALS

The study area can be divided into four subareas on the basis of geology and geomorphology: (1) Eroded Valley Terrain, (2) Stagnant Ice Terrain, (3) Washed Terrain, and (4) Draped Bedrock Terrain.

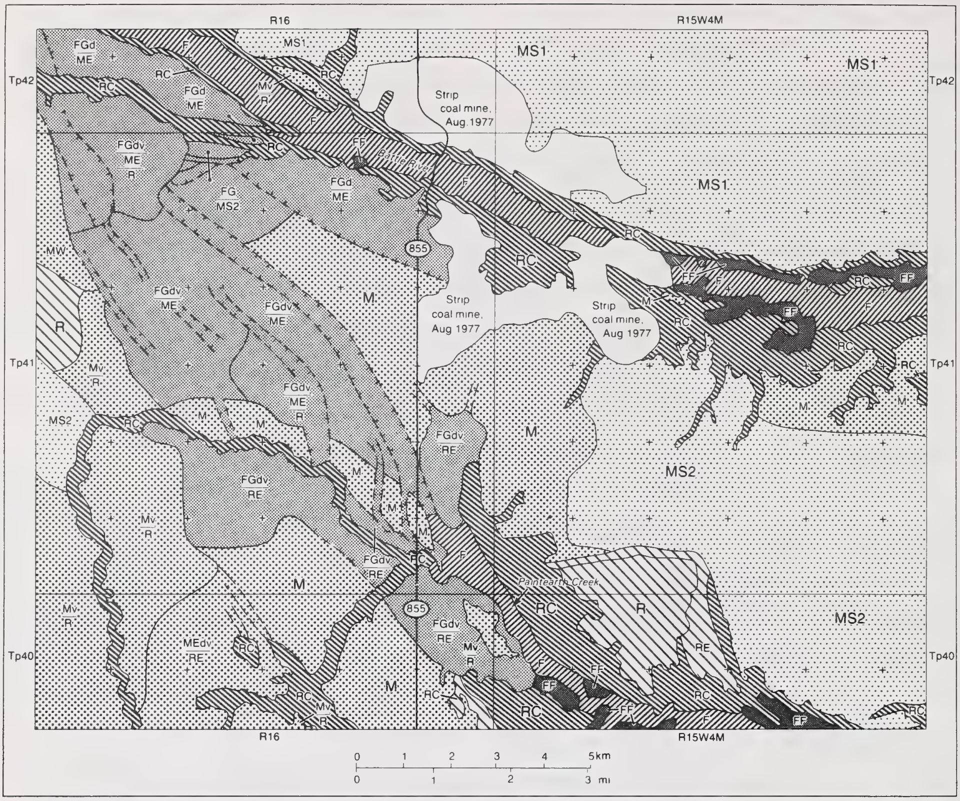
Eroded Valley Terrain: This subarea includes the valleys of the Battle River and of Paintearth Creek and its tributaries east of section 1, 40, 16 W4. The geology consists of recent fluvial deposits that form the valley floors (units F and FF, Figure 30), and eroded bedrock that is partially mantled by fluvial and colluvial sediment in the adjacent areas of badland terrain (units R and RC, Figure 30).

The fluvial sediment consists dominantly of loamy silt with significant amounts of sand and clay and minor organic material. It is generally less than 2 m thick in the valleys tributary to Paintearth Creek, but generally more than 25 m thick along Paintearth Creek and at least 70 m thick along the Battle River. Testholes show that the sediment filling these major valleys is fine-grained sand and sandy silt and clayey silt.

In many places, the sandstone, siltstone, and shale of the Horseshoe Canyon Formation, in many places, is mantled by either colluvium, fluvial fan sediment, or a gravel lag (units RC, RE, and FF, Figure 30). The topography is hummocky with numerous mesa-like hills or rounded knobs. The unit boundary is commonly marked by a nearly vertical cliff, especially on the south facing slopes, which are nearly everywhere vegetation free.

The upper portions of the slopes are generally debris free; the lower portions are covered by more than 3 m of colluvium and fan sediment. This material, which is massive to moderately well stratified and sorted, is composed of eroded fragments of sandstone, siltstone, shale and minor quartzitic and igneous clasts, and fragments of till, coal and ironstone fragments.

Stagnant Ice Terrain: This includes the area north of the Battle River and the area between Paintearth Creek and the Battle



Legend

Symbol	Description
F	Stream deposits; Clay to sand sized sediment with minor gravel and organic matter; layered, locally unbedded, flat to rolling <2m relief; generally, 2m thick but .30m in major channels.
FF	Fan deposits: form single fans or an apron at base of cliffs; bedrock material and minor till and crystalline clasts; moderately to well sorted and stratified; generally <3m thick.
FG	Fluvioglacial deposits: sand, minor gravel; mainly bedrock material in many places; reflects underlying topography. FGd discontinuous cover, 0-<3m thick; FGdv discontinuous veneer 0-<2m thick.
M	Moraine: sediment deposited by glacier; mainly till (mixture of clay to sand with minor pebbles to boulders); locally includes abundant bedrock material or sand lenses. Mv veneer <2m thick. Mdv discontinuous veneer 0-<2m thick.
ME	Eroded moraine: low relief, some or none of original morphology remains; till with local sand or gravel lag; generally <2m thick.
MS	Stagnant ice moraine: till, local fluvioglacial sediment; flat to hummocky; generally <6m relief. MS1: depressions; till generally >3 m thick. MS2: depression free; till generally <2m thick.
MW	Washboard moraine: subparallel ridges; low relief, <2m; mainly till, <2m thick.
RC	Bedrock with a discontinuous cover of colluvium. Colluvium: unbedded, poorly sorted clay to boulder size sediment; mainly bedrock material, minor till, fluvial or fan sediment; topography flat to hummocky; thickness 0-10m, maximum at base of slopes.
RE	Eroded bedrock: colluvium generally absent; hummocky, relief <10m.
R	Bedrock: sandstone, siltstone, shale, mudstone, minor ironstone and coal; flat; <100m thick.
⤳	Channel

Figure 30. Map showing the surficial geology of the Battle River study area.

River east of Highway 855. Both subareas are generally covered by more than 3 m of till (a poorly sorted mixture of sand, silt, and clay containing minor pebbles, cobbles, and boulders). The northern subarea is characterized by hummocky topography with many closed depressions or sloughs (map unit MS1, Figure 30) and the eastern subarea by hummocky topography that lacks most of the sloughs, (map unit MS2, Figure 30).

Washed Terrain: This unit includes most of the area in range 16 north of Paintearth Creek and south of the Battle River (map units FG, FGdv, ME, RE, and R, Figure 30). The major geologic units are (1) eroded till covered by a discontinuous veneer of fluvioglacial sediment and (2) bedrock covered by a discontinuous veneer of eroded till and/or fluvioglacial sediment. The moraine is generally less than 3 m thick. The low relief topography is flat to rolling. The meltwater channels (Figure 30) are generally erosional features less than 1 m deep. The exception is the terrain within 2 km of the Battle River where, in places, the fluvioglacial gravelly sand to sand gravel exceeds 2 m in thickness.

Detailed investigation in this map unit in sections 14 and 23, 40, 16 W4 reveal the presence of two separate beds of till separated by a layer of sand that is as much as 2.4 m thick. This sand, which crops out in road cuts where Highway 855 climbs out of the Battle River Valley, underlies an area of at least 8 km^2 immediately west of Vesta Mine. Although stratigraphic relations are obscure, this sand unit is likely the saturated sand that is exposed in the upper part of the highwall in the extreme western end of the Vesta Mine cut.

This terrain is the result of immediately post-glacial erosion of till and bedrock covered by a veneer of till. The meltwater flowed southeastward into Paintearth Creek and later, following additional ice retreat, eastward along the Battle River.

Draped Bedrock Terrain: This includes the terrain south and southwest of Paintearth Creek. The terrain is generally flat to low relief moraine that has been cut by a series of east-west ice marginal channels. It includes units MV, MEdv, and M (Figure 30).

Limited data indicate the till is generally less than 2 m thick in the west half and less than 3 m thick in the east half of the subarea. In some places the till within 1 m of the bedrock consists of more than 90% bedrock fragments.

The downstream two-thirds of the channels have undergone post-glacial erosion and are marked by steep cliffs exposing bedrock. The upstream portions, generally the east-west segments, are erosional channels composed of a discontinuous veneer of fluvioglacial sediment over till.

Glacially Thrust Features: Folded and faulted bedrock is exposed in many places in the cliffs along the creek and river valleys. This deformation is believed to have been caused by the glaciers that flowed over the area.

There is no obvious surface expression of these features. The folds are either shallow or truncated so the resulting land surface is everywhere level. The greatest observed depth of this deformation was 7 m, and, at that site, the base of the fold was not seen. In the subsurface, deformation has been detected at depths as great as 15 m east of Paintearth Mine in section 7, 40, 15 W4 where the upper split of the Paintearth Bed has been removed. In the western part of Vesta Mine in sections 13 and 24, 40, 16, W4, intensely disturbed overburden has been observed resting directly on the Battle River Bed at a depth of at least 20 m.

5.3 QUATERNARY HISTORY

As discussed above, no evidence has been found in the Battle River study area of any glacial events prior to the last glaciation. Undoubtedly, glacial disturbance of the bedrock surface and drainage changes, similar to those that followed the final deglaciation of the area, had occurred earlier, but evidence of them had been removed.

The last glacier that advanced over the area produced minor structural disturbance in the rocks of the Horseshoe Canyon Formation to depths as great as 15 to 20 m throughout the study area. There is no evidence that the valley of the Battle River or of Paintearth Creek existed prior to this advance in anything like its present form. The present valleys in the study area were either formed totally during final retreat of the last glacier or were significantly modified during this event.

As the continental glacier wasted back toward the northeast, the glacier margin retreated down the slope from the divide south of Caster. Once the margin was north of this divide, meltwater was ponded to form lakes between the higher land to the south and the ice mass to the north. These lakes formed and emptied quickly as the ice margin retreated. Relatively locally derived meltwater cut the series of minor anastomosing channels that dissect the terrain south of Paintearth Creek. Channels were occupied and then abandoned as lower outlets to the east were exposed by the retreating ice margin. The water flowed in a broad shallow stream over the land cutting minor channels and depositing the layer of sand above the lower bed of till west of Vesta Mine. It then spilled over a small divide into a minor tributary stream that drained around the ice to the east. As the meltwater spilled over the divide, the soft shale of the Bearpaw Formation in the valley floor was rapidly eroded to deepen the valley. The area contributing water to this stream increased as the ice margin to the northwest melted back and discharge increased. Headward erosion in the Paintearth Creek Valley extended the over-deepened valley westward.

The ice margin likely retreated north of the present Battle River to expose a lower tributary similar to the Paintearth Creek Spillway. The same process of headward expansion of that valley occurred as flow shifted to this lower outlet for a time before it was blocked by a minor re-advance of the glacier, which extended just to the north edge of the Paintearth Creek Spillway. The upper till unit west of Vesta Mine was deposited by this re-advance. The drainage was diverted back to the Paintearth Creek Spillway allowing headward erosion to extend the deep valley into section 1, 41, 16 W4. Final wasting of the ice margin back north of the Battle River allowed the flood of meltwater, which was enhanced by overflow from the Gwynn outlet of Lake Edmonton, to return to the Battle River Spillway. This huge torrent of meltwater quickly incised the Battle River trench to a depth of 130 m through the study area. The spillway developed until it was a continuous deep valley stretching from the Gwyn Channel at Leduc into the Battle River Channel south of Camrose and extending far to the east of the Battle River area.

This Battle River Spillway was occupied until continued ice wastage in the Edmonton area exposed lower outlets for Lake Edmonton north of the Cooking Lake Upland into the North Saskatchewan River system. When drainage along the Paintearth Creek and Battle River Spillways ceased, they were deep, relatively smooth sided trenches with floors 80 m and 130 m, respectively, below the adjacent upland surface.

Throughout the Holocene, these trenches were filled, largely with sediment eroded from the adjacent valley sides. Most of this badland development and accompanying sedimentation in the trenches was completed during the warmer drier hypsithermal period when the sparse vegetation cover resulted in extensive erosion throughout the plains of North America. Although much of this sedimentation involved alluvial fans growing out into the valley from the sides, significant lacustrine sedimentation also occurred in some places. Where a larger than usual fan developed, it served to dam up the stream flowing along the valley floor and create a lake. Through these mechanisms, nearly all the sediment eroded along the trench was trapped and accumulated as a fill that is 68.6 m thick at the Highway 855 crossing of the Battle River.

This deep incision of the Battle River and Paintearth Creek Spillways has been of great significance for the hydrogeology of the Battle River study area in two ways:

1. By creating steep topographic gradients it has created steep hydrologic gradients and drain conditions deep in the flow system;
2. The deeply incised fill beneath Paintearth Creek allows more ready access of recharge to deep aquifers.

The effect of these are to create an active hydrologic zone in which groundwater flow velocities are significantly greater than deeper in the system or in a similar area that lacked the deep drainage. These more rapid flow velocities combined with greater recharge have resulted in greater flushing of several of the aquifers and the presence of better quality water deeper in the system than is typical of much of east-central Alberta.

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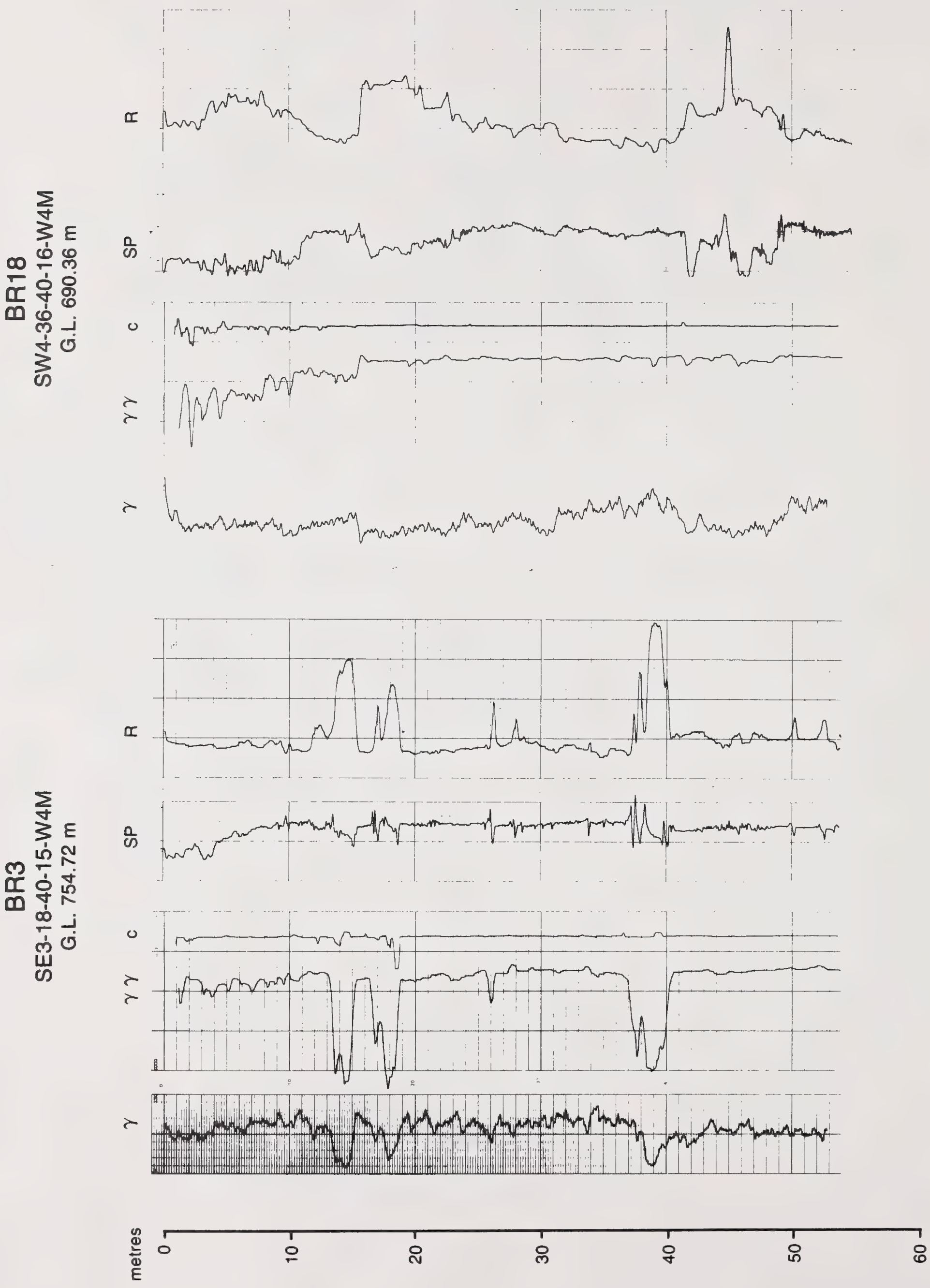
7. APPENDIX - GEOPHYSICAL LOGS OF BOREHOLES IN THE BATTLE RIVER STUDY AREA

7.1 EXPLANATION OF SYMBOLS

q = Natural Gamma Ray
qq = Gamma-Gamma Density
c = Caliper (one arm)
R = Resistivity
SP = Spontaneous Potential
n = Neutron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G.L. 690.36 m
BR3
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SP
R
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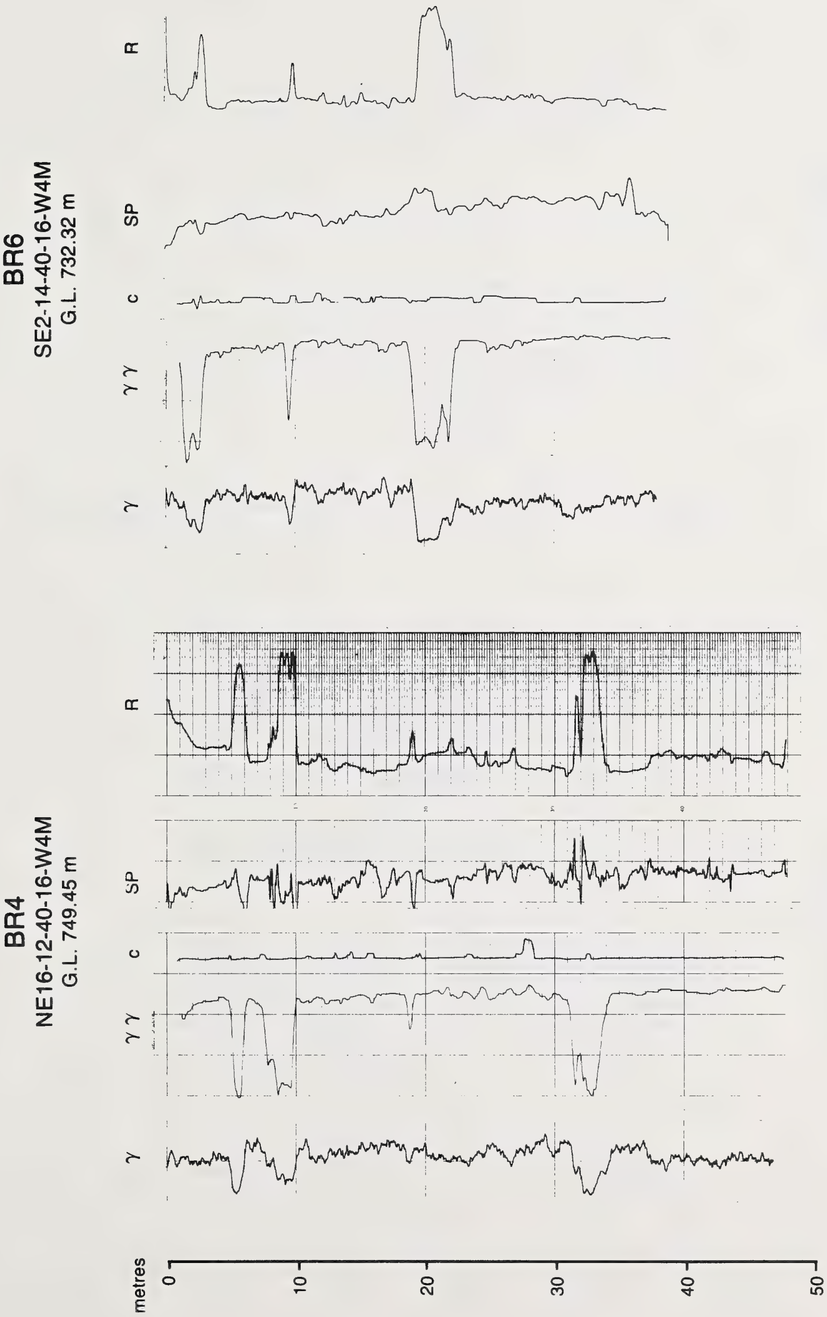
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SP
c
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γ
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SP
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metres
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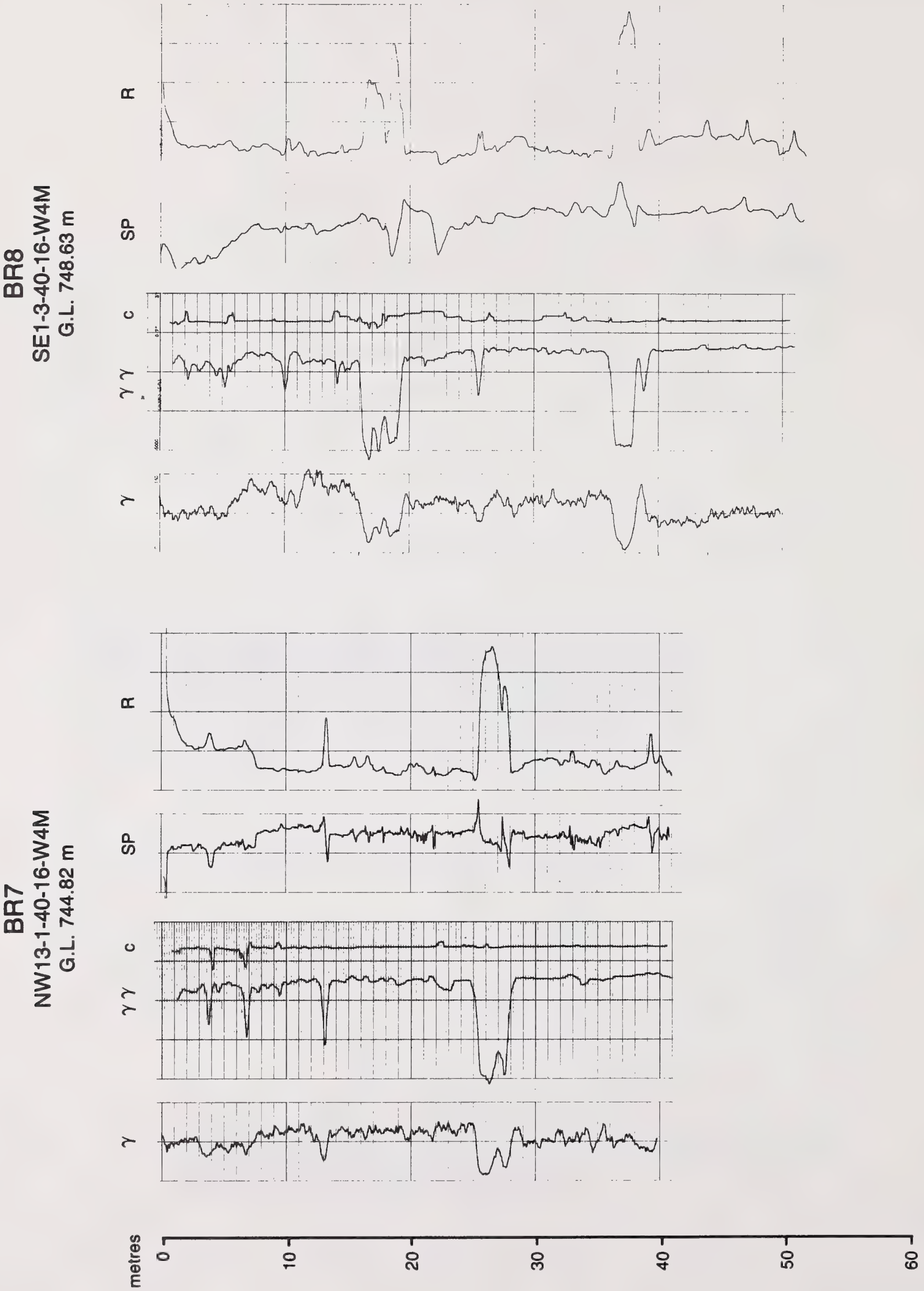
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R
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γγ
γ
BR7
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R
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γγ
γ
metres
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40
50
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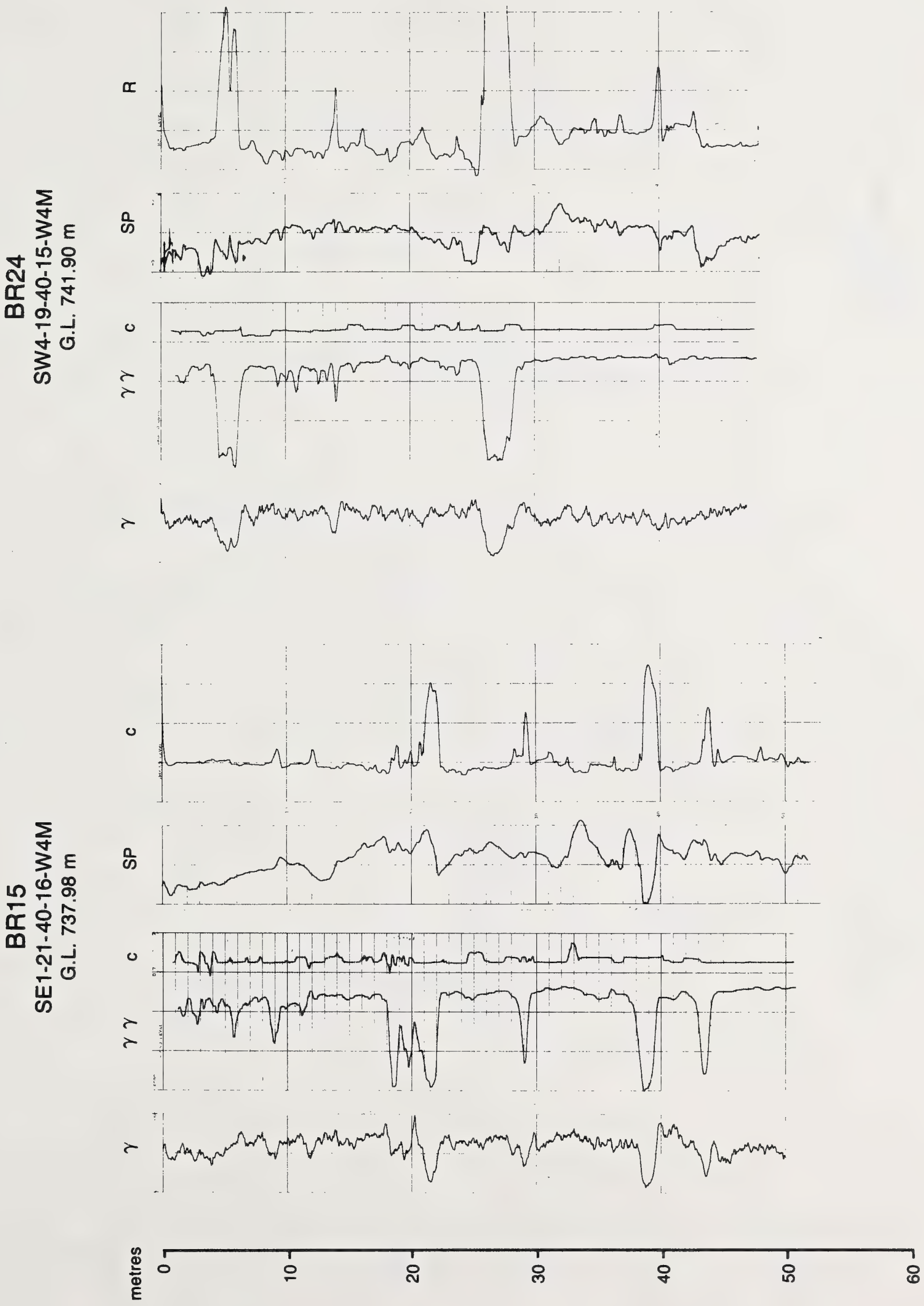
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γγ
γ
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SP
c
γγ
γ
metres
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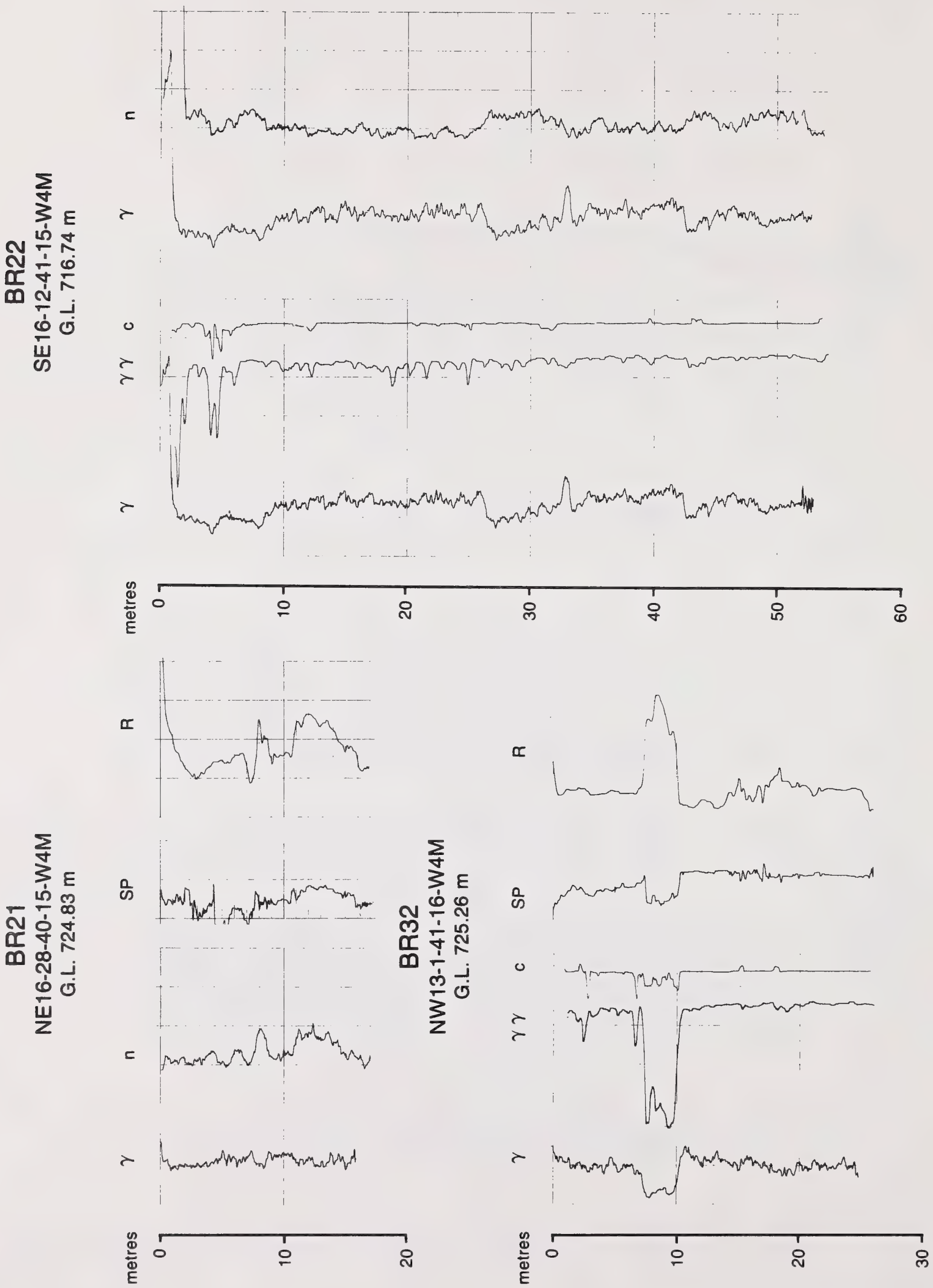
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c
γ
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metres
0
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20
30
40
50
60
BR21
NE16-28-40-15-W4M
G.L. 724.83 m
γ
n
SP
R
metres
0
10
20
BR32
NW13-1-41-16-W4M
G.L. 725.26 m
γ
γγ
c
SP
R
metres
0
10
20
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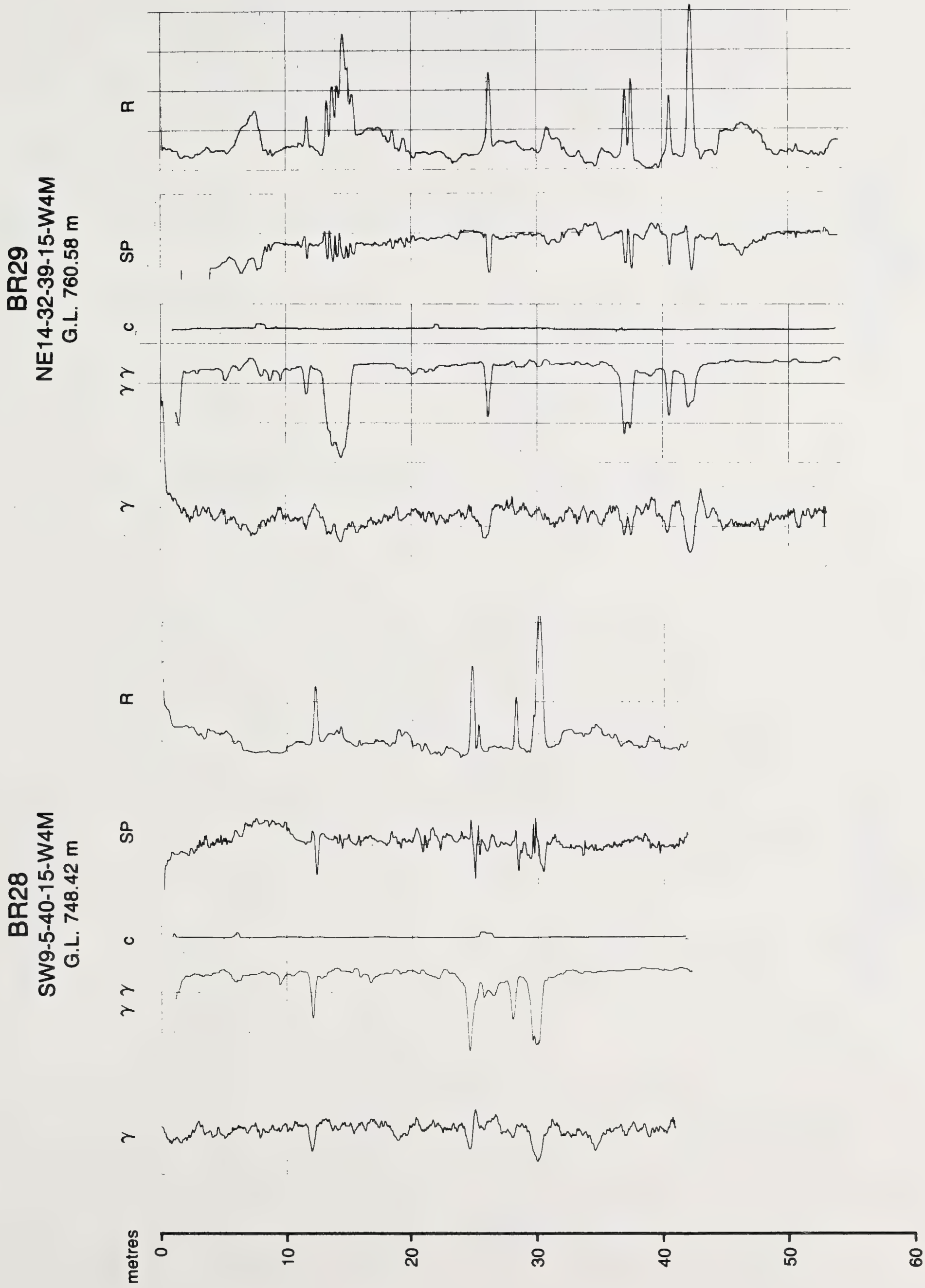
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γ γ
γ
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R
SP
c
γ γ
γ
metres
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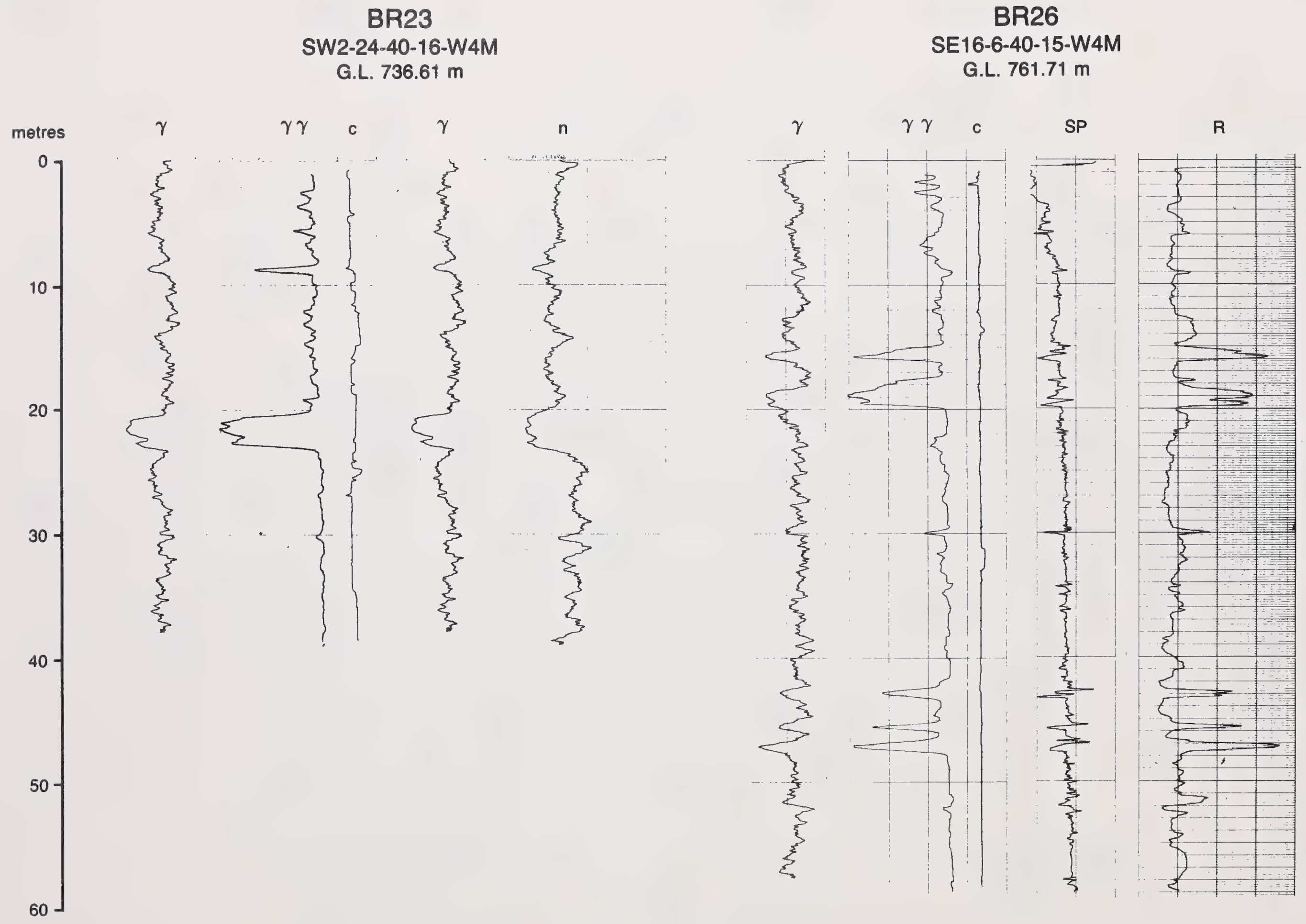
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SE16-6-40-15-W4M
G.L. 761.71 m
metres
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γ γ
c
γ
n
γ
γ γ
c
SP
R
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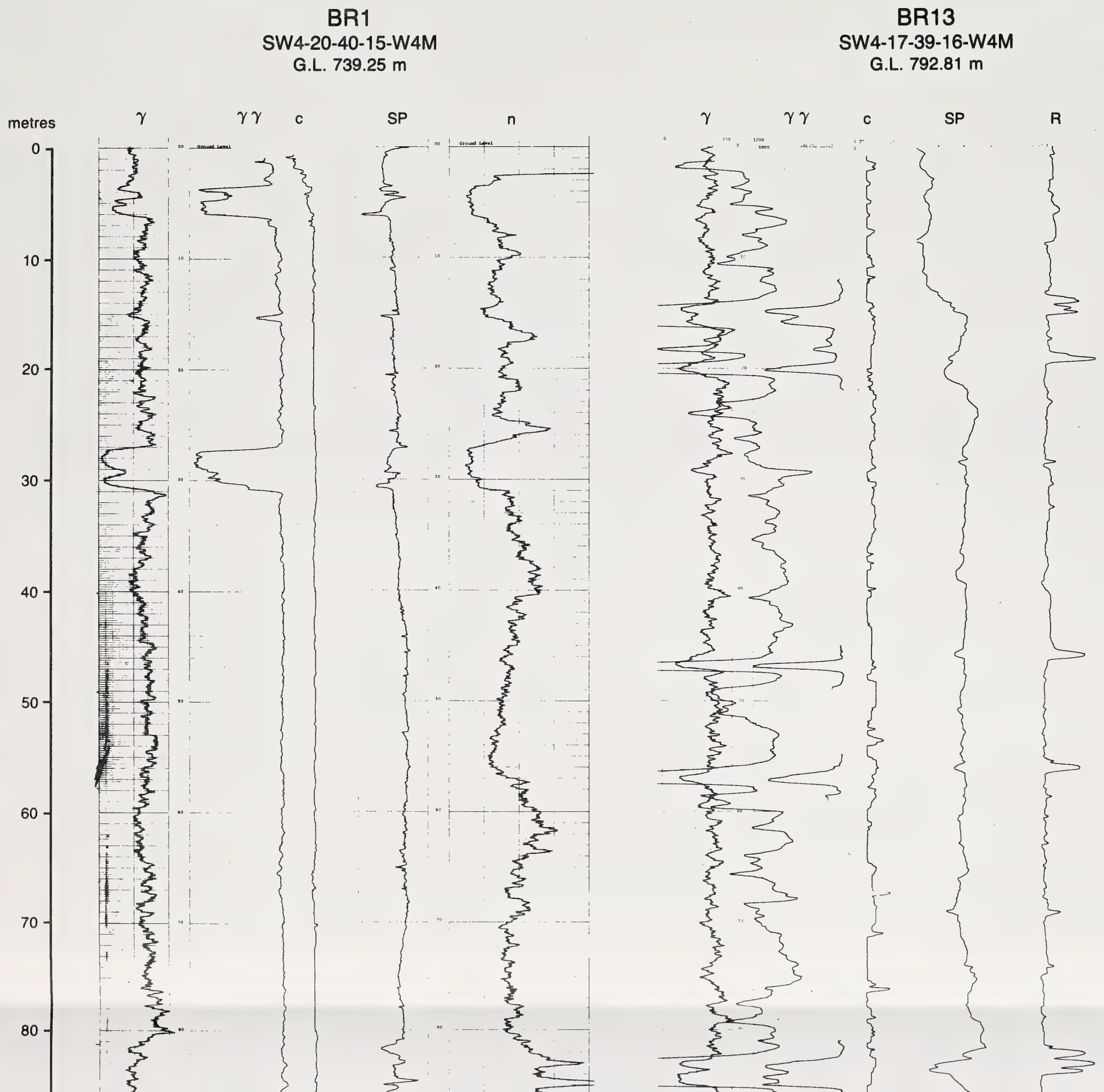

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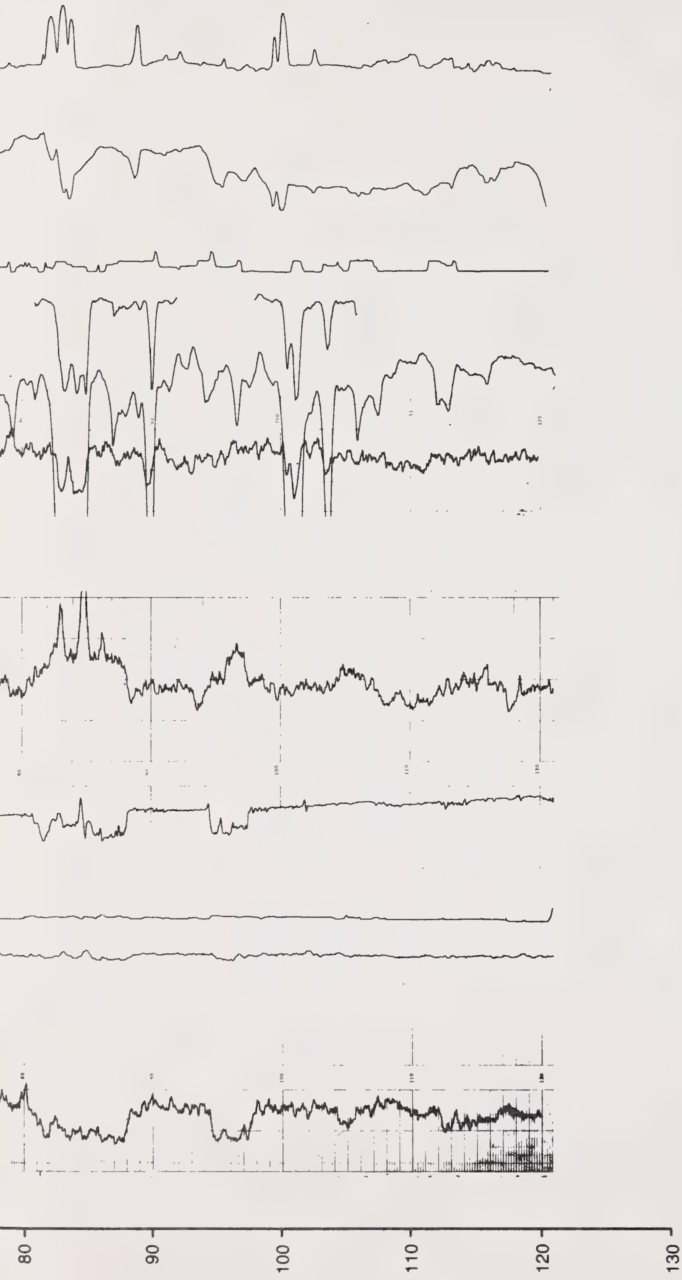
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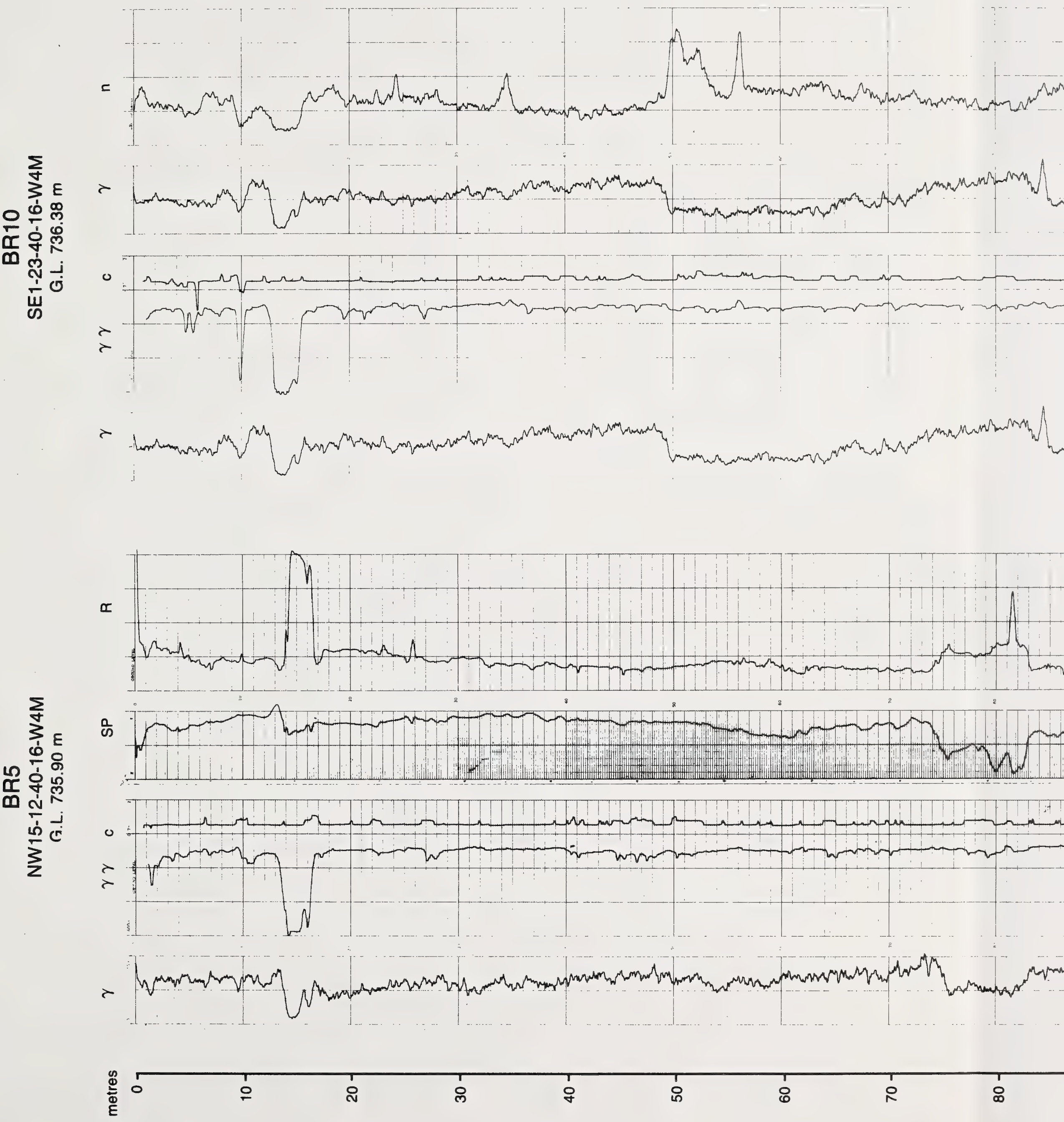
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γ
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γ γ
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BR5
NW15-12-40-16-W4M
G.L. 735.90 m
R
SP
c
γ γ
γ
metres
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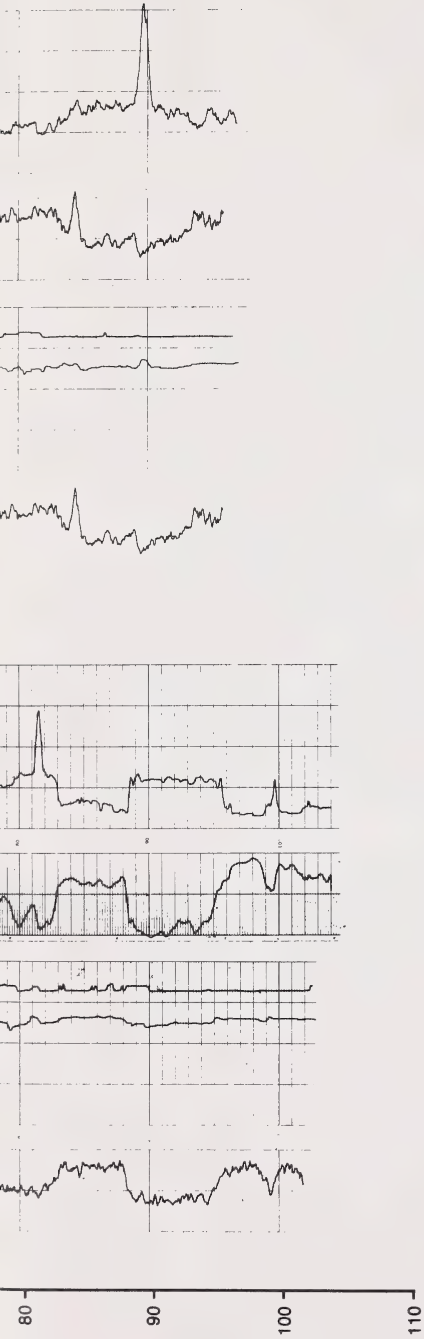
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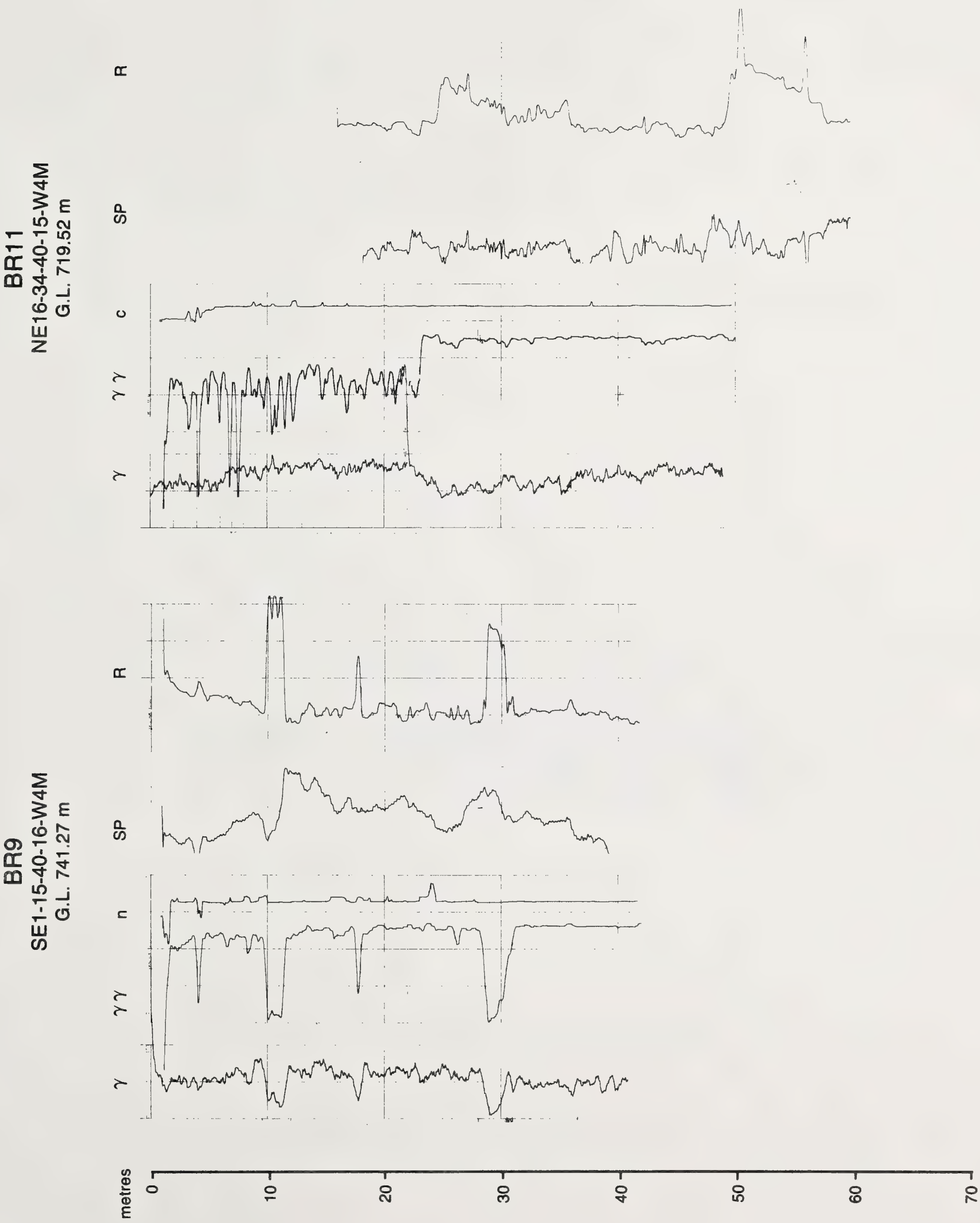
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γγ
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SP
R
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γγ
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R
metres
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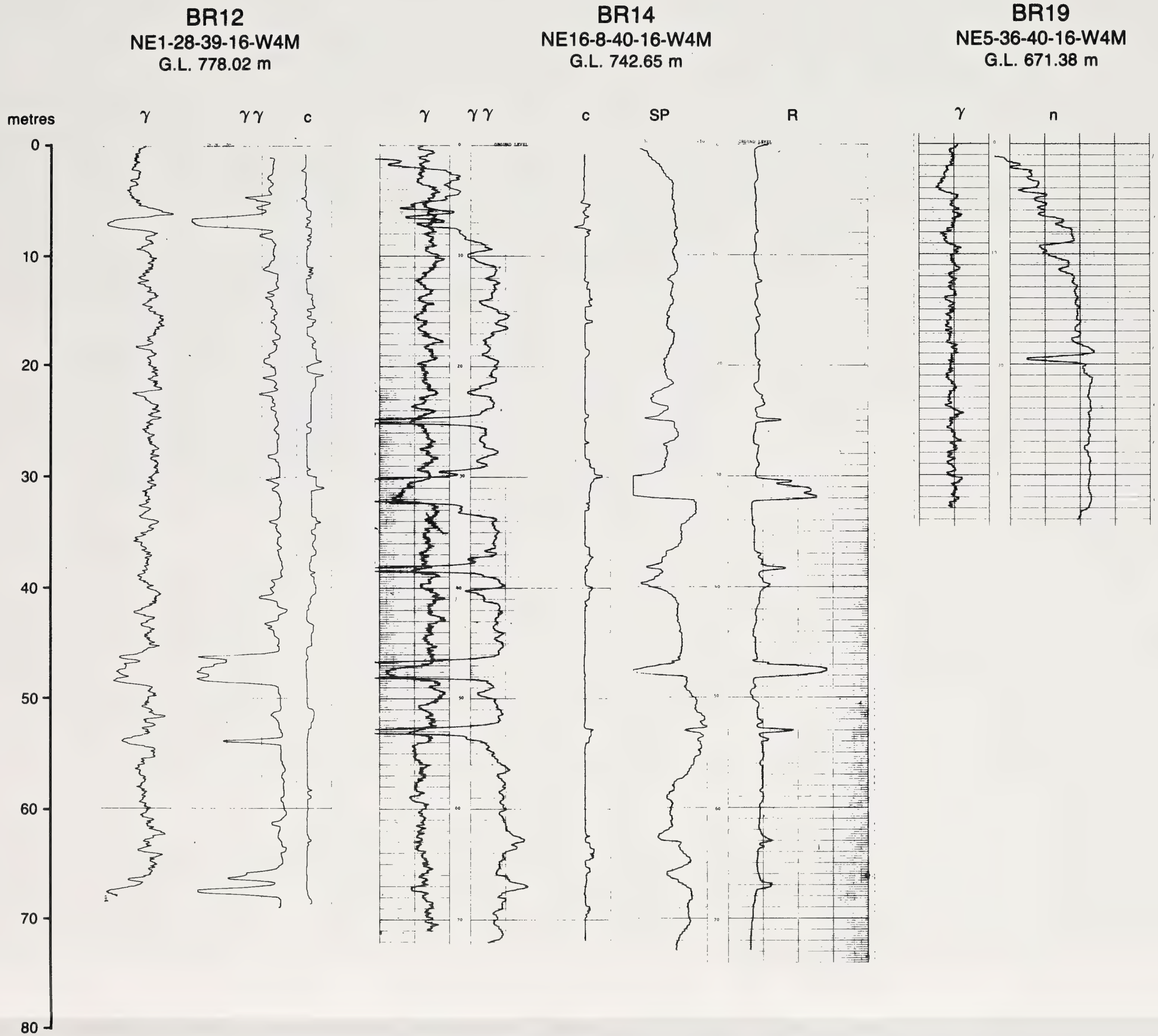
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G.L. 742.65 m
BR19
NE5-36-40-16-W4M
G.L. 671.38 m
metres
γ
γγ
c
γ
γγ
c
SP
R
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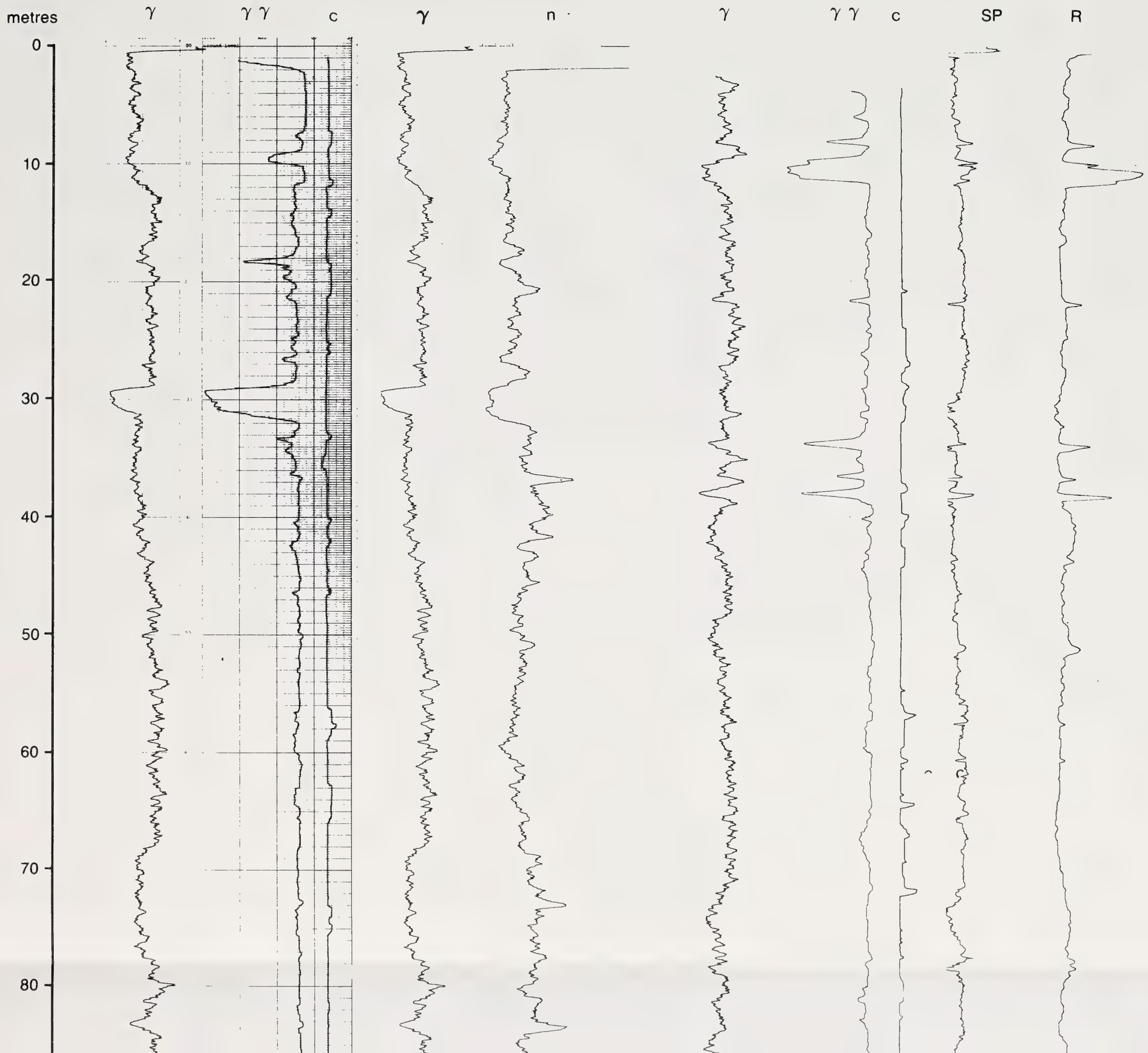

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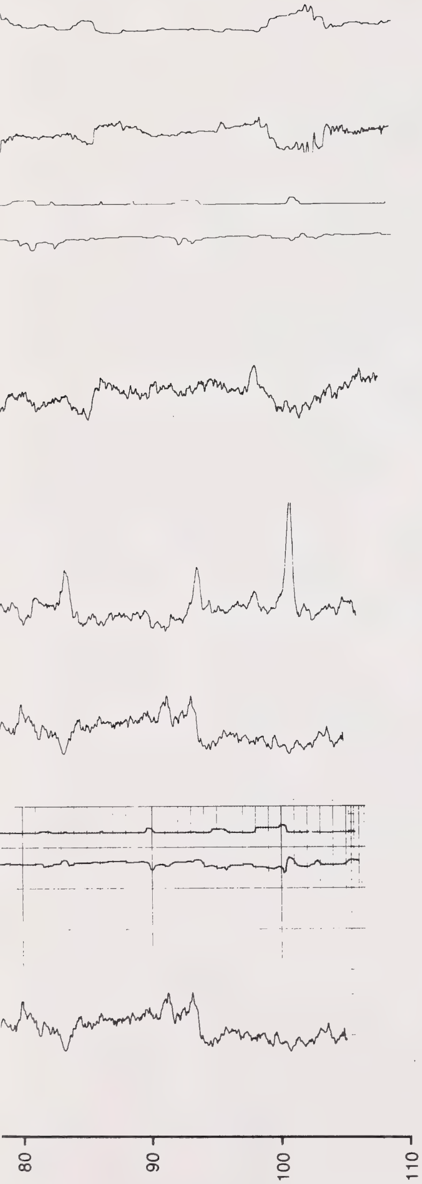
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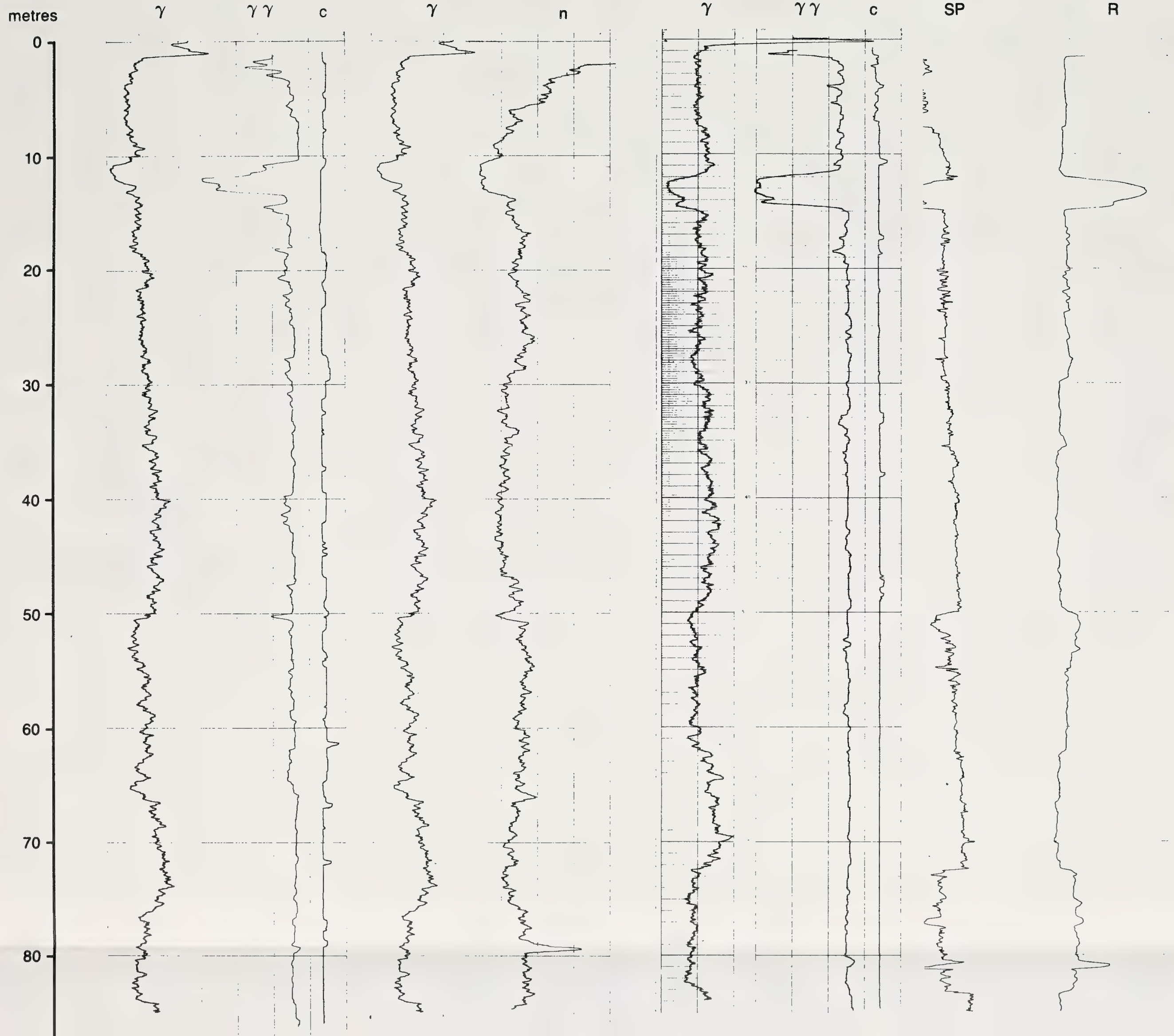

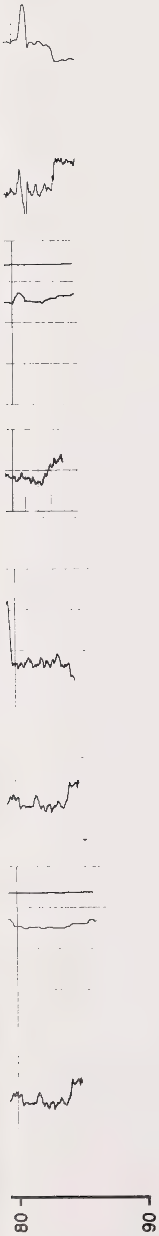
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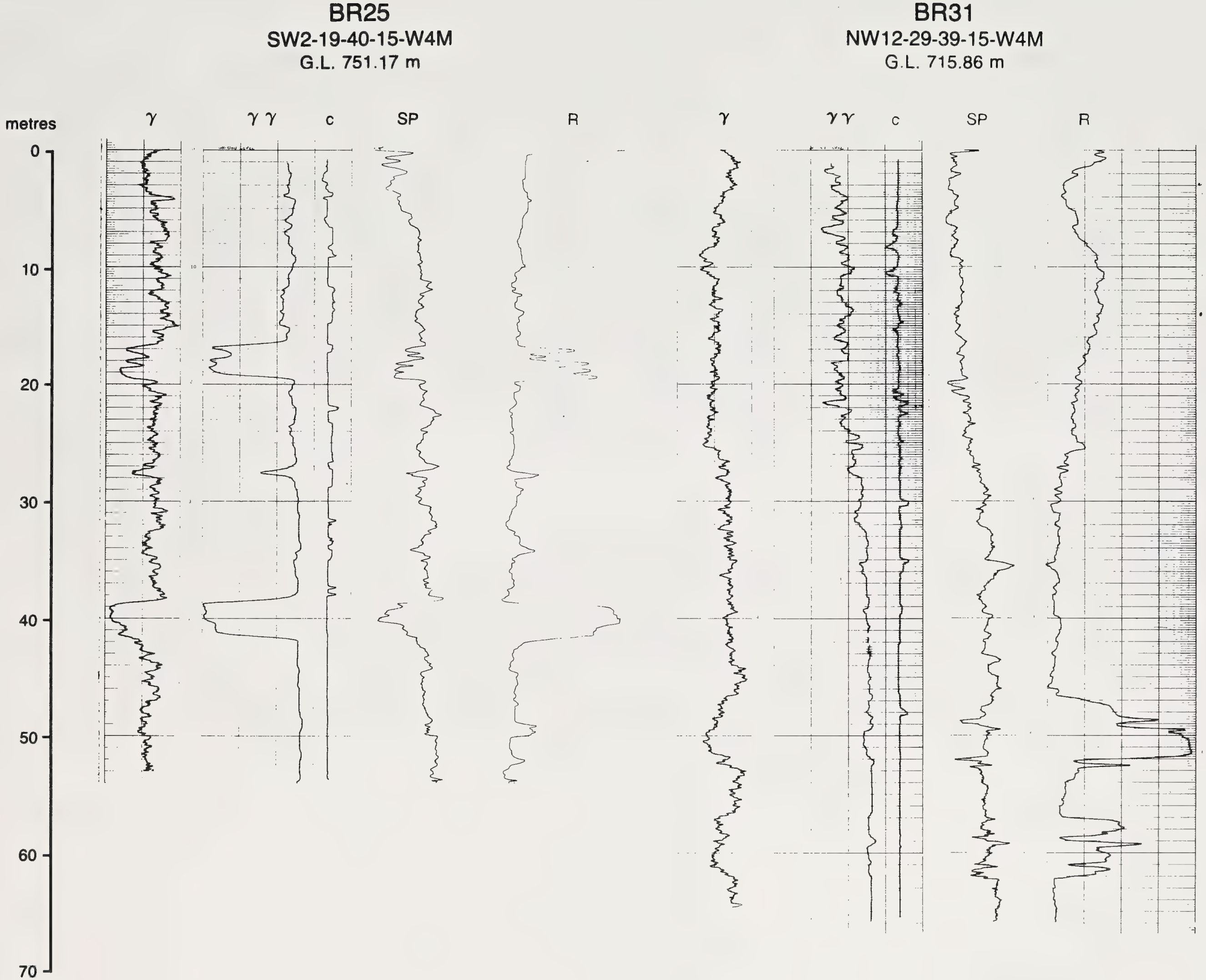
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G.L. 715.86 m
metres
γ
γ γ
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γ γ
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SP
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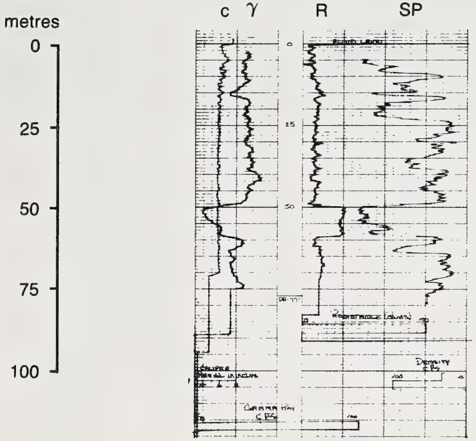
G.L.733.37 m



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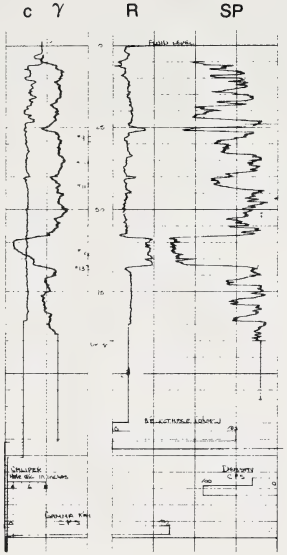

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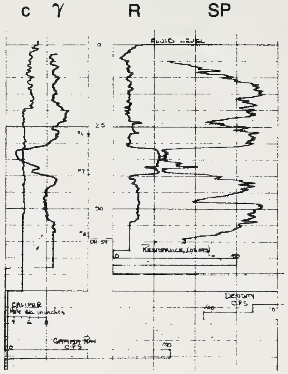

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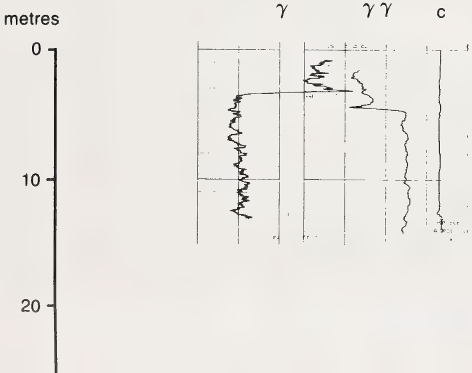

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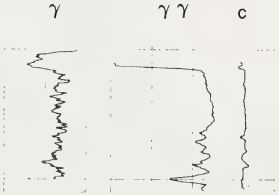

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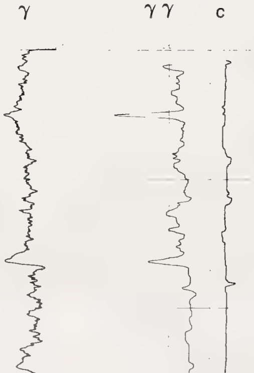

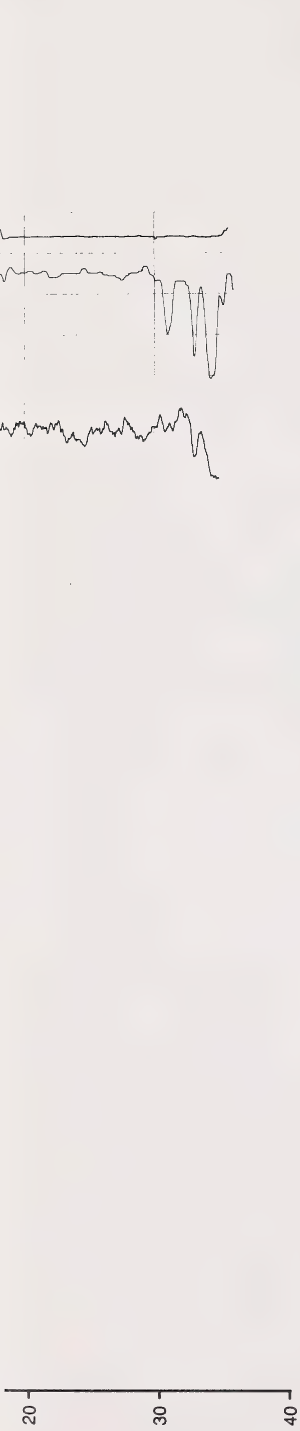
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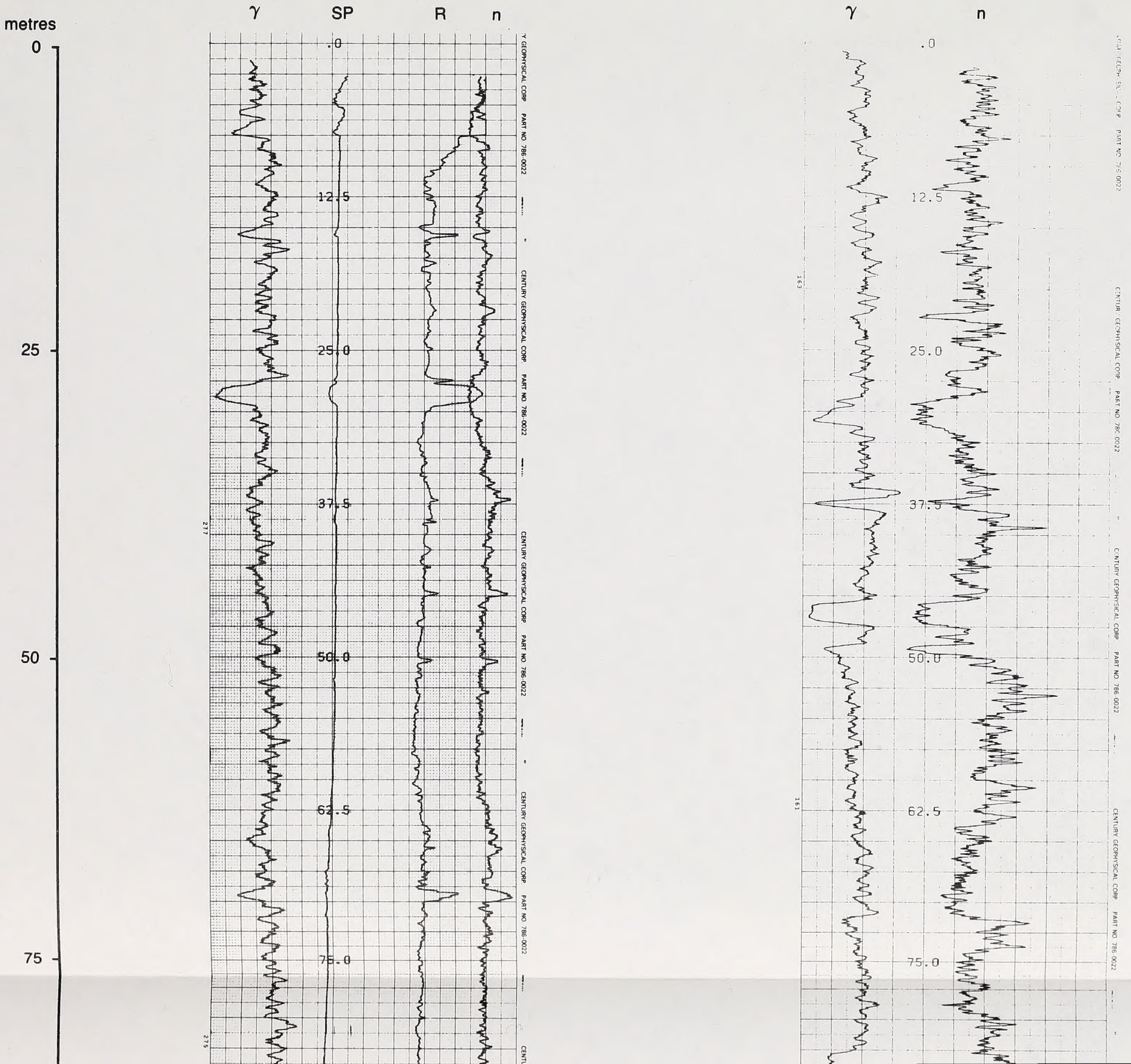

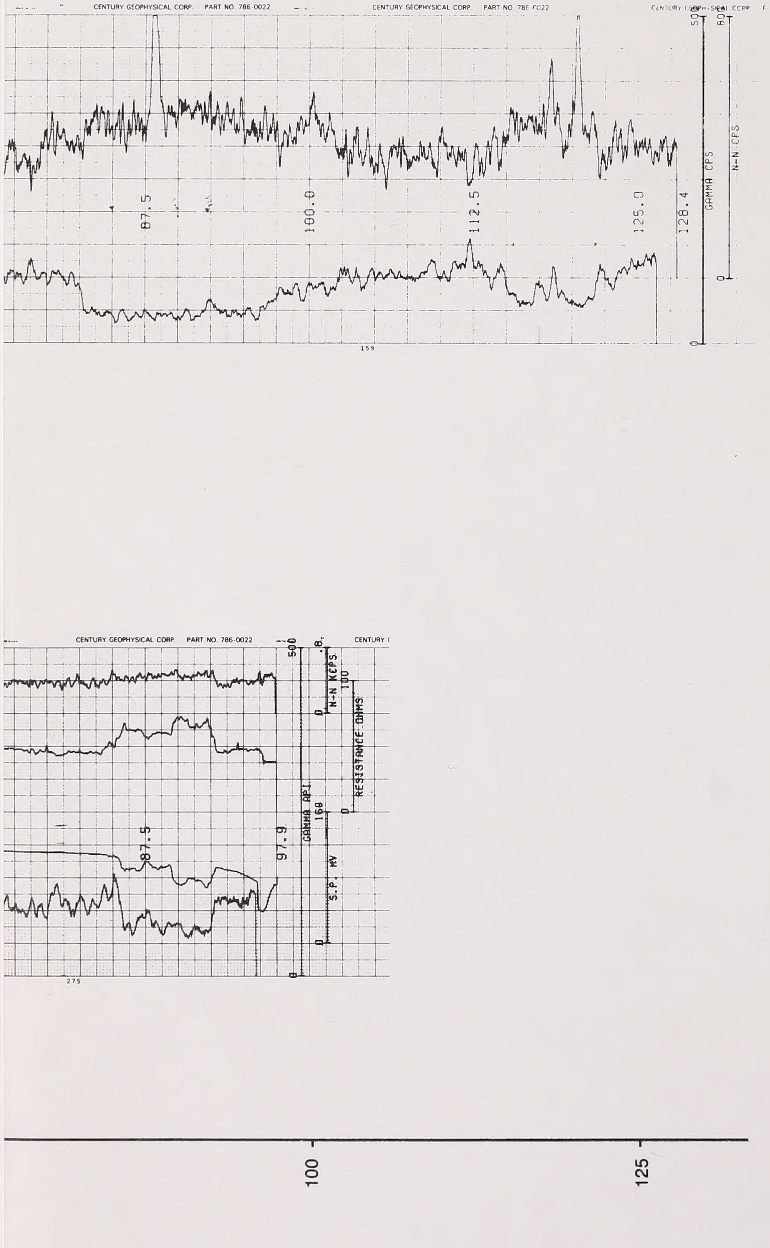
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